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NITINOL INTERCONNECT DEVICE FOR OPTICAL FIBER WAVEGUIDES

FINAL REPORT

A PROJECT OF THE
MANUFACTURING TECHNOLOGY PROGRAM
NAVAL SEA SYSTEMS COMMAND

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Two different interconnect devices for optical fibers have been developed. Each uses the shape memory effect alloy "NITINOL". The simpler of the two is of tubular design and accommodates fibers as small as 200 μm diameter. The more complex multi-component design accommodates 125 μm diameter fibers. The complex design is simpler to use, easier to manufacture and lower in cost. It permits less than 1 db loss and is re-matable. A description of NITINOL manufacture is given.

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FOREWORD

Recent breakthroughs in the science of optical devices have resulted in advancements in telecommunications technology. Worldwide civilian use of fiber optics in telephone communications is proving successful from both economic and qualitative standpoints.

For the Navy, fiber optic systems have certain special advantages beyond the favorable economics they offer in information transmission networks. For example, blue-green light travels well in sea water, potentially enabling communication with submerged submarines. Also, the decrease in the weight and quantity of cabling necessary for an on-board fiber optic communications system, would allow improved ship design and performance. These and other advantages support the Navy investment in development of fiber optic systems capable of meeting MIL SPECS.

For Naval applications of fiber optic systems, improvements in emitters, couplers and interconnects are desired. This report will focus on how interconnects may be upgraded through the use of NITINOL alloys.

The concept of a simple tubular connector for optical fibers, using NITINOL, was proposed by the Naval Ocean Systems Center (NOSC). The developmental work was funded by the Naval Sea Systems Command and performed by the Naval Surface Weapons Center. NSWC invented and pioneered the development of NITINOL shape memory alloys. These alloys can be deformed below a specific temperature and self recover their shape upon heating above that temperature.

In its original format, the work was an advanced extension of an existing manufacturing technology; however, with the advent of commercially available 125 micrometer (μm) fiber, a different design approach was required. As a result, a totally new interconnect device was invented.

This report will deal first with the development of the tubular connector prior to the improved technology and then with the development of the interconnect device suitable for the 125 μm fibers. The new connector meets the low loss, low cost objective set by the Naval Sea Systems Command.

W. CARSON LYONS
By direction

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Chapter 1

INTRODUCTION

FIBER OPTIC SYSTEMS

Optical fiber waveguide systems are now replacing copper wires in selected telecommunications installations. The economic breakeven point is a signal density of 9 megabits per second, or about 100 voice circuits.

Fiber optic systems have technical advantages for military systems beyond their economic attractiveness. Because of their significance a brief review of the advantages to the Navy are presented.

MERITS OF FIBER OPTIC SYSTEMS

To understand the principal driving force for the introduction of a fiber optic system compare its signal transmission capability with that of twisted pairs of copper wires: A bundle of eight optical fibers, about the diameter of a pencil lead, will transmit what now requires a 3-inch diameter telephone cable. Weight savings are equally remarkable. In addition to its small diameter and its low weight a fiber optic system also can provide:

- Submarine communication through a water interface.
- Bandwidths of hundreds of Mbit/s with present systems and hundreds of Gbit/s for future systems.
- Secure data transmission.
- Immunity to strong electrical or magnetic noise fields.
- Dielectric isolation between transmitter and receiver, ranging from a few feet to hundreds of feet.
- Negligible crosstalk between fiber-transmission elements.
- Lower loss than coaxial systems.
- Ultimately lower cost than either coaxial or twisted wire systems.

BACKGROUND OF NAVY INTEREST

The above merits are not unmitigated; there are problem areas also.

One concern is the high cost of interconnects capable of less than 1 db loss of signal strength. As an example, a currently popular interconnect (for commercial installations) retails at $100. The Navy objective, in addition to a more reasonable cost without sacrifice of quality, is that the interconnect perform in service despite shock, vibration and temperature extremes as now set by MIL Specs.

The Navy seeks, in essence, an analog to connectors for copper wires: low loss, low cost, physically rugged, operable over a wide temperature range, easily and quickly installable by unskilled technicians.

A candidate platform for an electro-optical (fiber optic) communication system at the start of this program was the last of the DD 963 class of Navy ships then (and now) under construction. An excellent review of a Shipboard Data Multiplex System, applicable to the DD 963 class, is given by J. A. Bollengeir of the Naval Postgraduate School[1].

OBJECTIVES

At the start of this program the objective was development of an interconnect for a 1200 m (48 mil) diameter fiber bundle, the then state of the art. Early in the program this was modified to match the rapid progress in development of good quality 250 to 200 μm diameter single fibers. Later the objective for this program was again changed to a connector for even lower optical loss fibers of 125 μm diameter. This diameter was capable of far higher bandwidths, i.e., greater message traffic, than the original bundles of fibers or the 200 μm single fibers and it appears likely to become an industry standard.

This last shift in objective required a totally different developmental approach. Whereas the initial objectives required an extension of an existing manufacturing technology, the last objective forced the development of a totally new device.

Development of other interconnects by both communications firms and component manufacturers was also proceeding apace for the commercial market[2]. These devices were primarily modifications of existing designs, frequently requiring increasingly precise and costly machining to accomodate the decreasing fiber diameters. Furthermore, these devices were oriented to the less stringent requirements of commercial applications. Thus, there was no assurance that they would meet military specifications.

[1]Bollengeir, J. A., "State-of-the-Art Fiber Optics and its Applications to the Shipboard Data Multiplex System," Master's Thesis, Naval Post Graduate School, Montery, Ca., Mar 1979.

[2]Dalgleish, J. F., "A Review of Optical Fiber Connector Technology," Proc. 25 Wire and Cable Symposium, Cherry Hill, N.J., 16-18 Nov 1976.

PROGRAM RATIONALE

The apparent limitations of other connectors made investigation of alternative devices more attractive. One new idea was to utilize the shape memory effect of the alloy NITINOL. This metal, as a thin strip or wire, can be easily bent or deformed at room temperature. Upon then being heated to 100°C it will self recover to its earlier shape. Other recovery temperatures can be selected by choosing alloy compositions slightly different from the nominal 55 weight percent nickel, 45 weight percent titanium. Additional details of the shape memory phenomenon are presented in Chapter 6. The Naval Ordnance Laboratory (now the Naval Surface Weapon Center) invented this alloy and was active in its development. Development of the connector device was to be performed at NSWC since:

- NSWC contains the NITINOL Technology Center.
- The NSWC mission is fleet support, including shipboard communications.
- The requisite NITINOL materials and technology were not available in private industry.

The Naval Ocean Systems Center (NOSC) recognized the potential of NITINOL as a shrink fit connector for F/O and was the first to propose it. Giannaris,* in 1976, conceived of tubular connectors for 48 mil diameter glass fiber bundles and 10 mil diameter single fibers using a shrink fit metal in a manner analogous to shrink-fit olefin plastic tubing. Giannaris believed that NITINOL, with significantly higher strength and stiffness than an olefin, would provide a rigid, durable connector. His conclusion was supported by prior research at NSWC demonstrating the shape memory recovery of NITINOL in the micron size range: A specimen of NITINOL had been metallographically examined after hardness measurements with a Tukon diamond hardness tester. These microscopic indentations became smaller after the NITINOL was warmed, demonstrating micro-dimensional response.

NSWC concluded that a sub-hypodermic size tube would indeed shrink in diameter and, if made with sufficient precision, could serve as a connector for 10 mil fiber optic wave guides. Production of suitable short length miniaturized tubes would require rather sophisticated manufacturing technology. This was based on past experience which had shown that it is difficult to drill or draw NITINOL by conventional processes. Further, this difficulty was experienced in the more easily worked larger sizes, as opposed to the thin wall, small diameter tube sought here. This machining difficulty is due to the very high rate of work-hardening intrinsic to NITINOL.

Following coordination with CDR Giannaris, D. Williams and R. Kochanski of NOSC a developmental program was agreed upon with the objective of producing prototype connectors for preliminary insertion loss measurements. The connector design selected was to provide for easy installation, have low electro-optical loss, be rugged, durable and operable in all environments specified by the military for communications equipment and be low in final cost. It was also agreed that development of the original 48 mil diameter fiber bundle connector would be superseded by a 10 mil (~250μm) diameter single fiber connector objective. This recognized the probable emergence of

*CDR Giannaris, R. J., USN, NOSC, San Diego, CA, Private Communication.

single fibers as the dominant wave guide for future communications applications. An approximate 8 mil diameter fiber (DuPont PFX S120R) was selected as the candidate fiber for coupling and optical loss measurements.

PROGRAM PLAN

A program consisting of the following sub-tasks was considered to be an orderly and low risk method of producing 10 mil diameter single fiber connector prototypes. The sub-tasks for the tubular connectors were designated as:

(1) Fabricate connectors by axial micro-drilling of wire.

(2) Fabricate microtubing from seamless heavy wall tube.

(3) Fabricate microtubing from rolled and welded sheet.

(4) Demonstrate functioning prototype connectors and test for resultant optical loss.

(5) Produce NITINOL with shape memory recovery between -75° and -55°C.

Results of this part of the Program Plan are presented in Chapter 2.

When the objective subsequently became the 125 μm interconnect the program plan was modified to:

(1) Operate the interconnect using a 125°C heat source instead of a refigerant (e.g., freon).

(2) Design the interconnect for manufacturing and installation ease.

(3) Produce thin gage NITINOL strip with memory recovery at 110°C.

Results of this part of the Program Plan are presented in Chapter 3.

Chapter 2

TUBULAR DESIGN INTERCONNECTS

FABRICATION OF TUBULAR INTERCONNECTS

SUB TASK 1: CONNECTORS BY MICRODRILLING. Single fiber optical wave guides typically range from 5 to 10 mils in diameter. The initial efforts were therefore aimed toward producing a connector with a 10 mil hole along the axis of a cylinder 1/8 inch long. Connector blanks were produced from NITINOL wire ranging in size from 15 - 20 mils diameter. The blanks were then supplied to vendors skilled in the art of microdrilling for hole generation. These vendors required starting pieces with ends that were flat, normal to the axis and burr free. Two techniques for producing the required precision cylindrical blanks were developed. The first consisted of potting strands of wire in the bore of a small glass tube with epoxy resin. After the epoxy had cured, the glass tube was cut into the desired length using a diamond saw. The glass was then broken and the cylinders were separated from the epoxy using a razor blade as a wedge to cleave the cured resin. This technique was generally successful although it was found necessary to remove some "burr" or "wire edge" from the ends of the cylinders.

Deburring was accomplished by lapping the ends on a fine bench stone. The pieces were held as shown in Figure 1. A fixture was made using the tailstock spindle of a jeweler's lathe to grip the specimens. Collets are available in increments of .05 mm (~2 mil) and the small cylinder is gripped in the appropriate sized collet with a length equalling approximately one wire diameter protruding. The spindle is in turn inserted into a brass holder whose bore is an easy slip fit for the spindle and whose base is machined normal to the bore. The assembly is then placed on a hard Arkansas honing stone, lubricated with cutting oil, and lapped until the desired finish is achieved. Several sizes of finished blanks and drilled connectors are shown in Figure 2. The smallest are 10 mil diameter x 40 mils long while the largest are 20 mil diameter x 80 mils long. These are shown standing on end to illustrate the excellent flatness and burr free condition achieved. The lapping technique proved so effective that the potting and sawing method was abandoned and subsequent blanks were made simply by cutting to approximate size with pliers and then lapping both ends to finished size.

The blanks were drilled by electrical discharge machining (EDM) after initial efforts using mechanical drilling proved fruitless. Several techniques were tried by different vendors and the best results were achieved by rotation of both the workpiece and electrode. Pieces produced when the workpiece remained stationary were generally of poorer quality with problems in straightness and roundness of the bore quite common. Early yields of acceptable pieces averaged only about 10-15% of those worked.

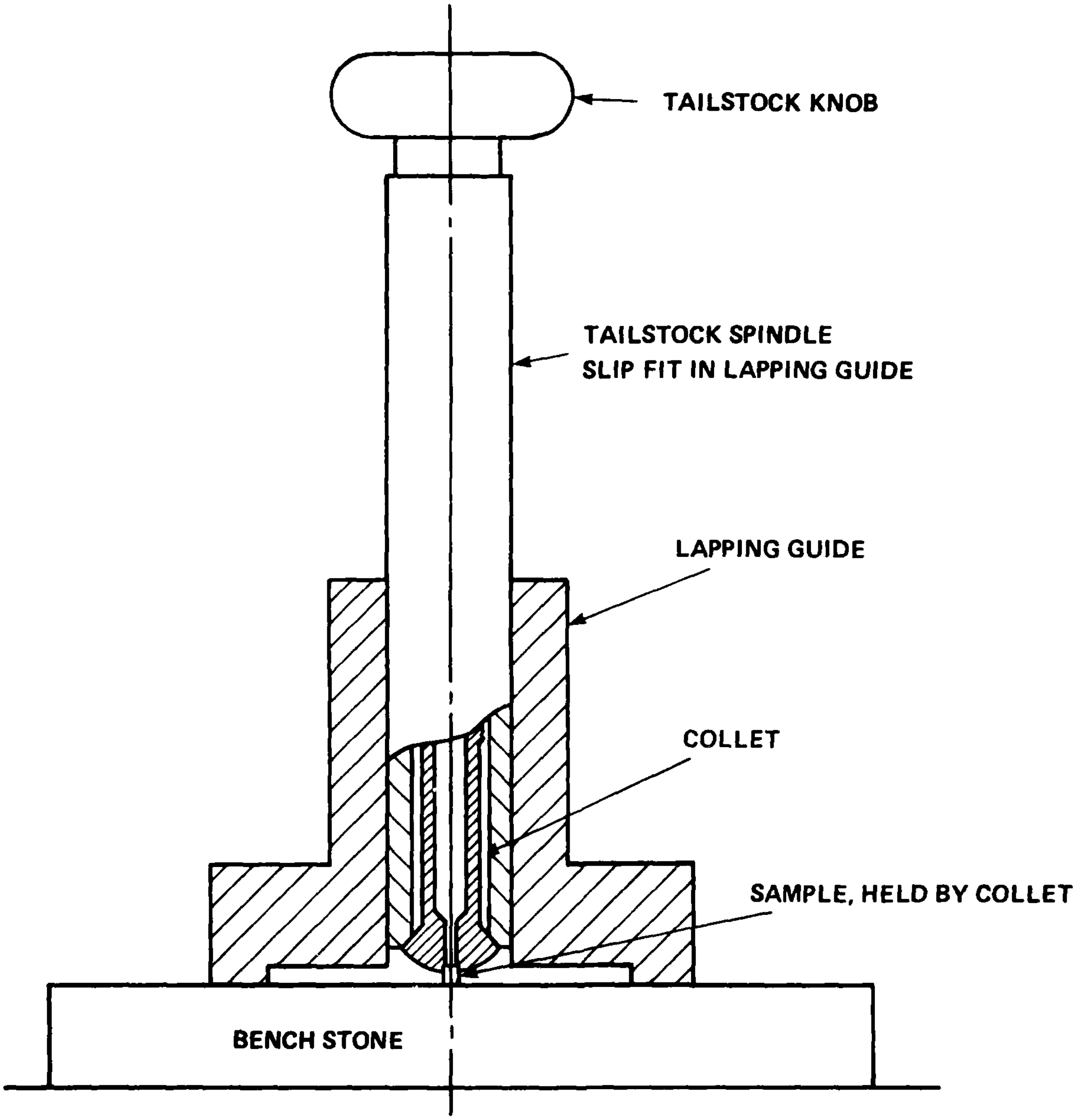


FIGURE 1 FIXTURE FOR LAPPING

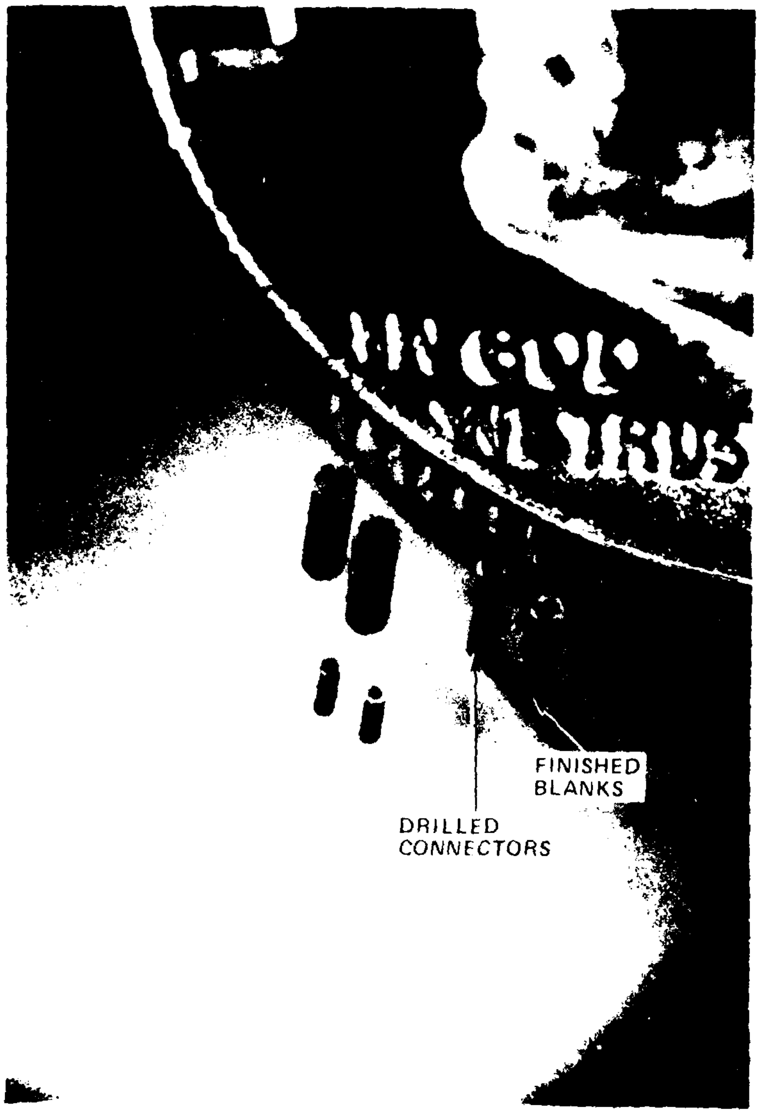


FIGURE 2 CYLINDRICAL CONNECTOR BLANKS AND DRILLED CONNECTORS

Figure 3 shows the cross-section of one of the dual-rotation-drilled connectors. These have been finished to tolerances of ±.0002" on both the concentricity and bore size. Drilling was done from both ends and the absence of any mis-match at the center is testimony to the precision of the drilling technique.

Expansion of these micro-tubes required some modification of the mandrel technique normally used with larger bores. The main difference is that the mandrel was pulled rather than pushed through the bore using the fixture shown in Figure 4. The pulling fixture is the tailstock of a jeweler's lathe which has been fastened to an aluminum base plate in line with an assembly which holds a small draw plate. The center of the draw plate has been drilled slightly larger than the size of the mandrel to be used. The mandrel has a thinned down forward section which is passed through the coupler and gripped by the tailstock collet. Force on the tailstock lever pulls the mandrel through the coupler thus enlarging the bore.

Mandrels are formed from steel music wire in the following manner. A short length of wire (~3") is pointed by immersing in a nitric acid-alcohol mixture (NITAL) until etched sufficiently to fit through the smallest die to be used. The wire is then progressively drawn through diamond wire drawing dies until the desired mandrel size is achieved.

The lead end of the mandrel is further reduced by additional drawing which is stopped before the whole mandrel length is pulled through the die. Pulling the mandrel back through the die leaves the desired configuration of oversized end with reduced lead in. The technique is illustrated schematically in Figure 5.

The process is continued through smaller and smaller dies until a lead-in size is attained that will readily pass through the unexpanded sleeve. Two completed mandrels are shown in Figure 6.

The NITINOL connector gripping force has been measured by shrinking it onto a steel wire and measuring the load necessary to slide it along the wire. The force is, of course, a function of the temperature and above the transition temperature of the NITINOL, forces as high as 3500 gm (7.7 lb) have been recorded. Below the transition, the force drops to nearly zero indicating that for durable joints the transition temperature of the alloy should be less than the lowest anticipated operating temperature.

Sub Task 2: Seamless Microtubing. The conversion of heavy wall seamless tubing into smaller diameters by tube drawing is common practice for steel. If similar processing is applicable to NITINOL, it offers a straightforward procedure for generation of microtubing. It was therefore worth considering before engaging in more laborious methods of tube production.

On this premise five ingots of NITINOL were cast in a nonconsumable electrode copper hearth furnace to the dimensions 5/8 inch in diameter by 4 inches long. These were swaged in air at 850°C to an outside diameter of 0.48 inch. They were then axially bored commercially using Electrical Discharge Machining (EDM) to provide a concentric 0.25 inch diameter hole. A single draw through a tungsten carbide die was achieved successfully on the

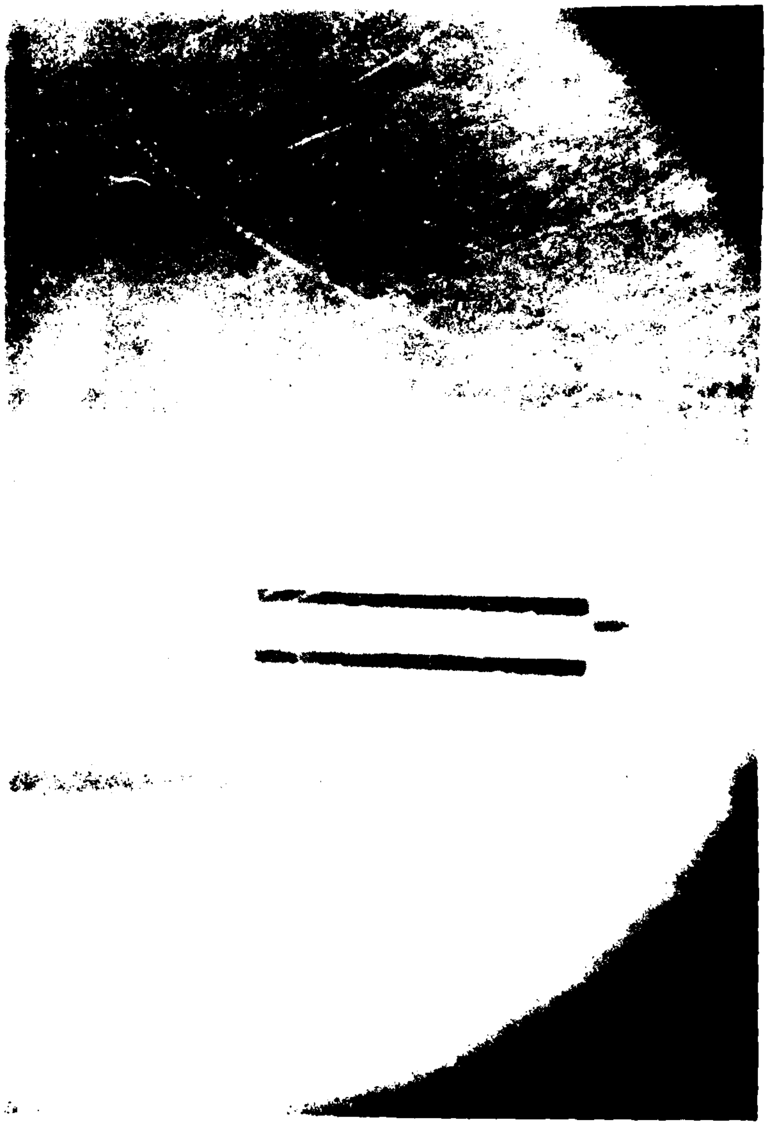


FIGURE 3 CROSS SECTION OF DRILLED CONNECTOR

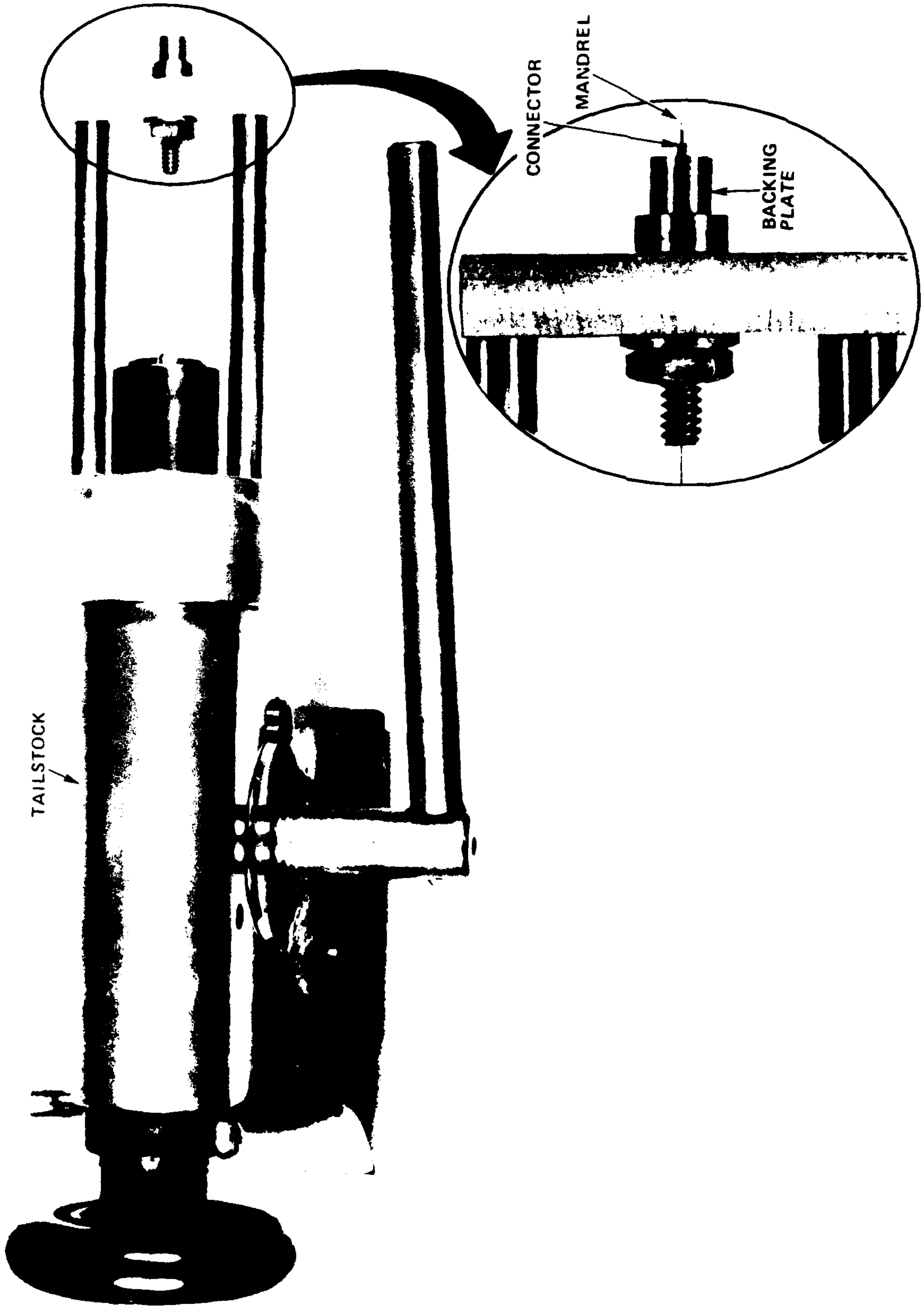


FIGURE 4 CONNECTOR EXPANSION FIXTURE

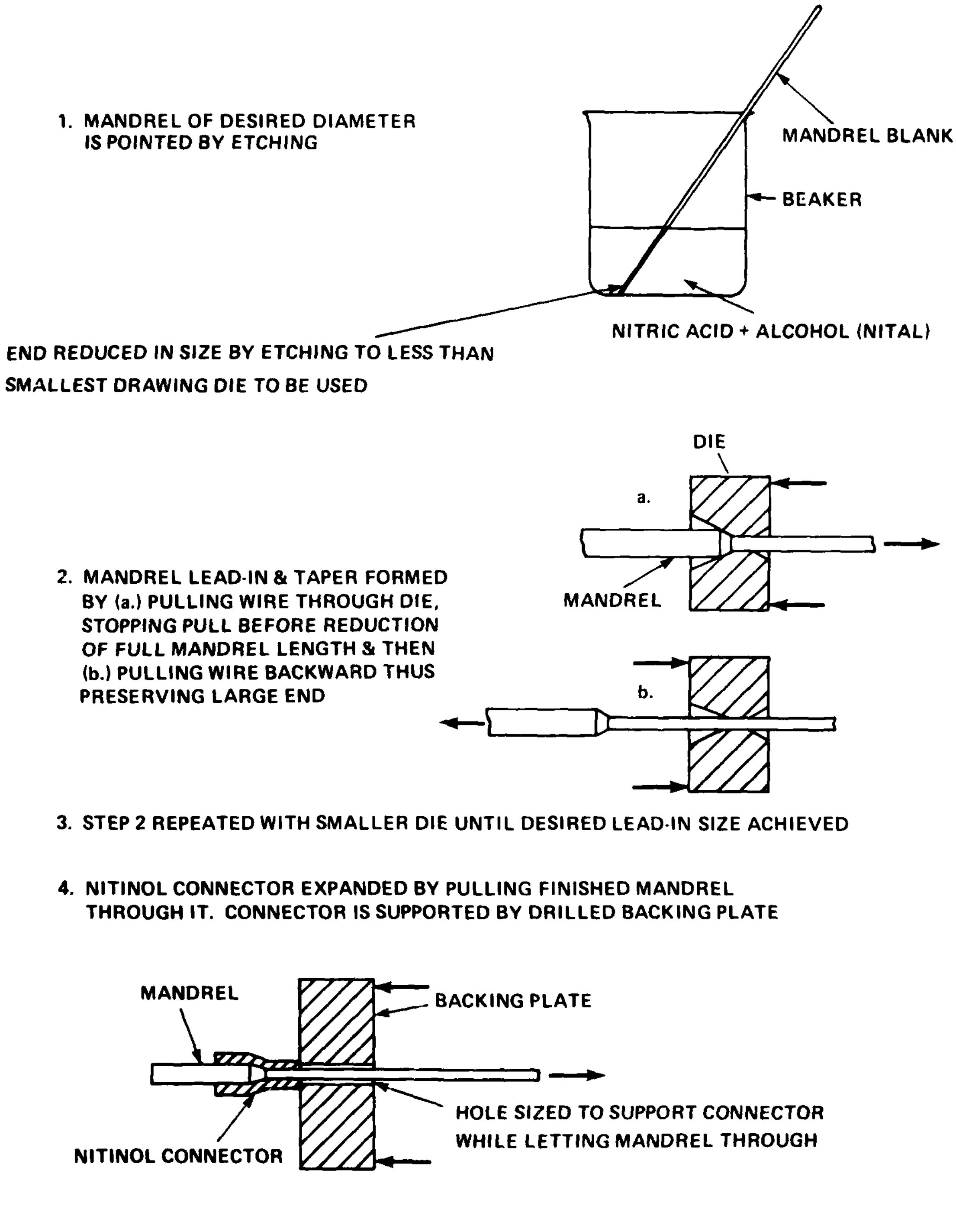


FIGURE 5 MANDREL FORMING SEQUENCE AND CONNECTOR EXPANSION

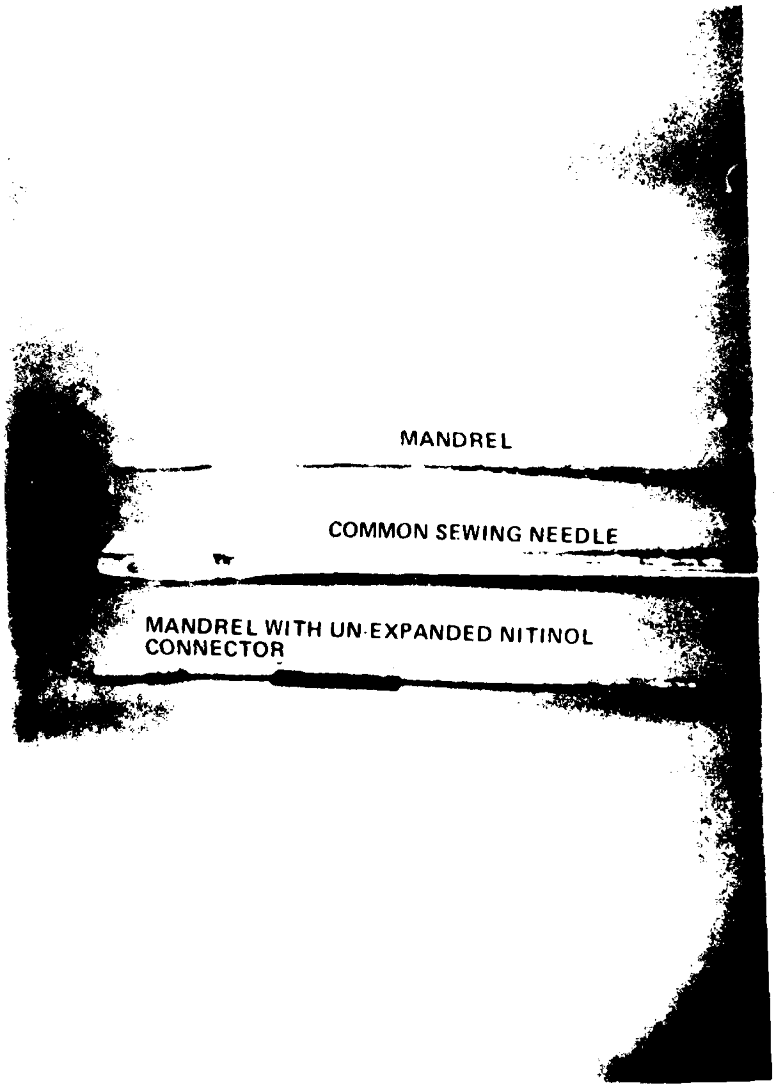


FIGURE 6 FINISHED MANDRELS

first tube, but subsequent draws on it were not. Despite annealing between draws the leading end of the tube continued to break off during redraw attempts. It was concluded that a thinner wall tube was more likely to be successfully redrawn.

The second bored seamless tube was hot swaged. Although the outside diameter was reduced no wall thinning was obtained. This precluded conventional swaging as a means of reducing wall thickness for this tube.

A third heavy-wall tube was hot swaged after supporting it on a cold L-605 alloy mandrel. No significant reduction in wall thickness of the NITINOL resulted. The heated NITINOL tube had greater hot strength than the cold L-605 mandrel.

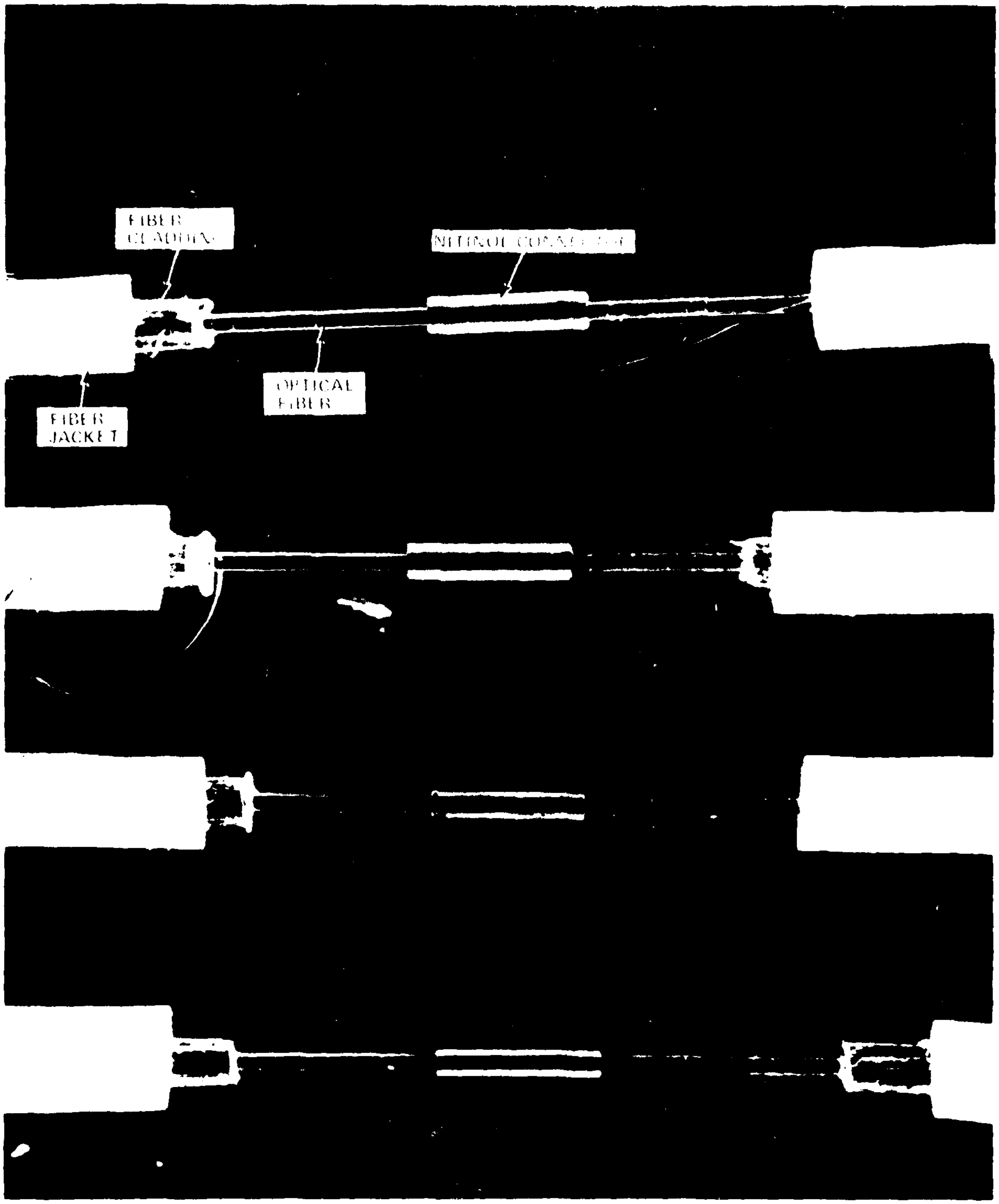
It was decided to discontinue this effort until additional seamless tubes with thinner walls could be prepared.

Sub Task 3: Welded Seam Microtubing. Tubing is commercially produced by forming strip into a tubular shape and butt welding the edges in a continuous seam. This technique is applicable to producing NITINOL tubing, subject to the restriction that welding must be done in an inert atmosphere or in vacuum. This restriction results from the rapid oxidation of NITINOL in an air atmosphere at melt temperature.

Strips of NITINOL were formed into tubular shape and then welded by electron beam operating in a vacuum. No filler rod is used, thus avoiding potential change of composition of the base material. The strips were of various thickness, between 0.024 and 0.080 inch. They were welded commercially, forming nearly round ~0.8 inch diameter tubes. Metallographic examination of the seam weld indicated a typical cast structure for TiNi. The 0.080 inch wall tubing was hot swaged, indicating swaging is feasible for tube production. The thinner wall tubing contained an incomplete weld penetration which failed during warm swaging. It appeared probable that 0.024 inch wall tubing can be swaged.

Additional strip was seam welded and subsequently extruded using a "filled tube" extrusion technique. This technique consists of placing a Hadfield steel mandrel inside each NITINOL tube and inserting this "filled tube" into a cavity within a mild steel casing. Multiple cavities exist in the mild steel casing such that 4 or 5 NITINOL tubes can be extruded simultaneously. Initial diametral reduction was 3:1. The extruded tubes retain their shape integrity. This extruded tubing becomes the preform for subsequent swaging and/or drawing operations to produce micro-tubing. One extrusion has been completed during the work period of this report. Swaging and drawing operations of the filled tubes are scheduled for the planned continuation of this effort.

Sub Task 4: Prototype Tube Connector Demonstration. Typical NITINOL connectors joining 10 mil diameter fibers are shown in Figure 7. To connect a pair of Valtec PC 10 fibers a connector with an inside diameter of 10.5 mils was selected. After a 4.75% expansion (to 11.0 mils) it accepted the optical fibers of 10.6 and 10.7 mils diameter respectively. Following gentle warming


FIBER
NITINOL
OPTICAL FIBER
FIBER JACKET

with a soldering iron tip the NITINOL shrunk and coupled the two fibers. Total fiber length was 10 meters. Preliminary tests at NOSC indicated 1.5 db loss in one direction and 0.9 db loss in the opposite direction. Variations in loss as a function of transmission direction was thought to be due to non-matching fiber ends. The ends were less than optimal due to inexperience with "bend and scribe" techniques customarily used for fiber end preparation.

The optical loss was not verified due to accidental breakage of the coupled fibers before a duplicated test could be performed.

No optical index matching fluid was used in this prototype coupling. It is presumed that improved ends on the test fiber will reduce the coupling loss significantly.

PERFORMANCE REVIEW OF TUBULAR INTERCONNECTS

The simple NITINOL shrinkable connector previously described has drawbacks which limit its use as a practical fiber optic connector. The advantages and disadvantages of the shrink fit tubular connector are:

Advantages	Disadvantages
1. Provides accurate alignment of equal sized fibers	1. Primarily suited for permanent splice
2. Strong gripping force	2. Limited size fiber acceptance
3. Small size gives potential for compact assemblies	3. Small size makes routine handling tedious
4. Economical via high production tube-drawing	4. Relatively expensive in small quantity batch processing
5. Stable, non-corrosive material	5. Cyrogenic expansion and assembly awkward

The most serious disadvantages are the need for refrigeration during tube expansion and assembly and the limited size acceptance of the connector. This limit requires fibers with very precise diametral tolerances (which are only now being introduced to the market place). The limitation on fiber diameter acceptance is dictated by the deformation properties of the NITINOL and the small size of the device. To be specific, complete shape or size recovery of deformed NITINOL can be expected at strains up to 8%. For a 125 μm (.005") diameter fiber, however, this leaves only a 10 μm (.0004") tolerance range to accommodate expected deviations from nominal fiber sizes. Consideration of the tolerances required by the manufacturer of the fiber and sleeve connector, assembly tolerances, and the requirement that the NITINOL sleeve not be severly overstrained as it shrinks onto the rigid glass core lead to the conclusion that the simple tube connector is impractical for the size range (125 μm) dictated by emerging fiber cable technology.

Chapter 3

TRI-SEGMENTED DESIGN INTERCONNECTS

TRI-SEGMENTED CONNECTOR CONCEPT

Many potential applications of shape-memory alloys would benefit from a "two-way" memory effect, i.e., a recallable memory both below and above the transition temperature range (TTR). The existence of a two-way memory would allow the simple sleeve connector to open and close repeatedly and greatly enhance the utility of such devices. Experiences with NITINOL indicates that memory alloys can be "trained", by repeated cycling, to exhibit reversible behavior but routine methods of achieving this effect have not been established.

In lieu of utilizing "two way training", it is practical to bias a device, e.g., by using the mechanical energy stored in a spring, to effectively yield an operating cycle. This technique has been used in other NITINOL applications and is utilized now in the Tri-segmented connector.

The concept is shown in Figure 8. In practice it consists of three identically sized, rectangular NITINOL strips and a thin walled beryllium copper (BeCu) tube. The NITINOL strips are given a flat memory anneal and then individually bent, while at a temperature below the TTR, to an angle of approximately 120° with the bend axis centered between the long edges of the rectangular pieces. The three bent strips are inserted into the bore of the tube as shown. The cavity formed by the three contiguous bends defines the location of the fiber splice. The material and dimensions of the tube are chosen so that the circumferential stiffness is adequate to maintain the NITINOL strips in a tight configuration when the NITINOL is below its TTR. When the device is heated through the TTR of the NITINOL, the strips attempt to return to their flat, or memory shape. This enlarges the central cavity, Figure 8b and allows the optical fiber to be inserted. The partial straightening of the strips also causes the tube to distort into a three-lobed shape. The distorted configuration is stable as long as the NITINOL remains above its TTR. After the source of heat is removed and the NITINOL strips cool, they revert to their martensitic or low modulus phase. This allows the elastic energy stored in the BeCu tube to force the NITINOL to bend more tightly and close down on the fiber which was inserted in the cavity, Figure 8c. The useful upper temperature limit of this device is set by the TTR of the particular NITINOL alloy used in fabricating the strips. NITINOL alloys can be formulated with no-load transition temperature ranges from cryogenic to about 110°C. However, the transition temperature of a NITINOL alloy is increased if the material is under an external load. The load vs. transition temperature effect is quite pronounced and reported data, as

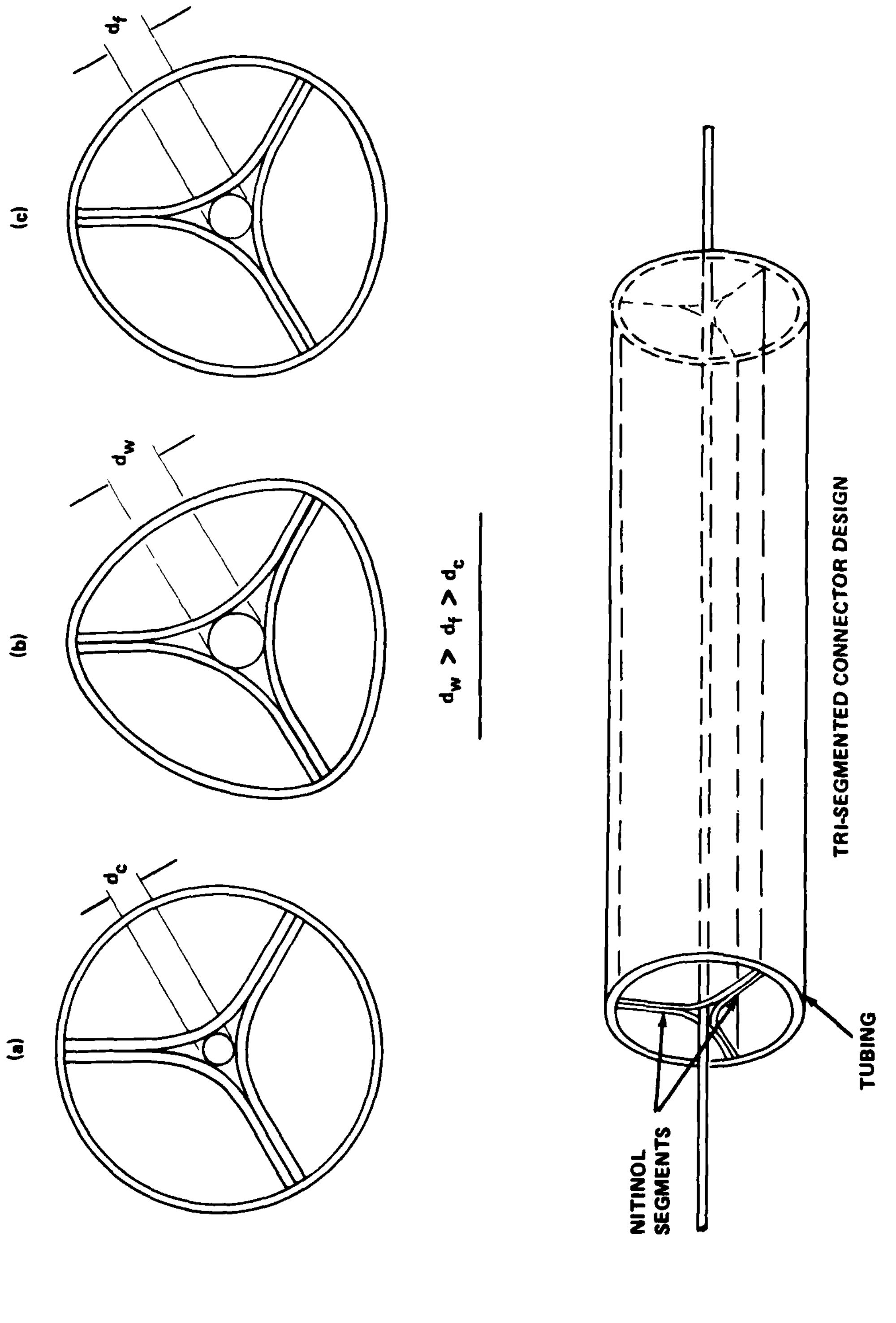


FIGURE 8 TRI-SEGMENTED CONNECTOR DESIGN

presented in Figure 9, show an increase in transition temperature from 40°C → 160°C for a particular alloy, as the stress was varied from 0 → 75 ksi. Thus, it is reasonable to predict that the upper temperature range for this device, configured as shown*, is about 125°C with the proper choice of NITINOL alloy and mechanical preload.

*It would be feasible to substantially extend the operating temperature limit of the device by reversing the position of the materials used in the connector, i.e., by using a NITINOL tube with three partially bent strips of BeCu or similar flat spring material. In this variation, the transition temperature of the NITINOL would be chosen to be below the minimum required operating temperature. To open this device, it would be cooled below the TTR where the restrained spring segments would force the NITINOL tube to distort and enlarge the cavity. As the connector warmed, the NITINOL would revert to the circular memory shape and force the spring segments into a tighter bend. The upper temperature limit for this variation would be ~300°C.

CONNECTOR DESIGN

For reliable, repeatable connector performance the following design criteria should be observed:

1. Strains occuring during tube distortion should not exceed the elastic strain limits of the tube material.

2. Strains in the NITINOL should be kept within the range of 6 → 8%. Data[3] have shown that the mechanical work output of NITINOL peaks within this range.

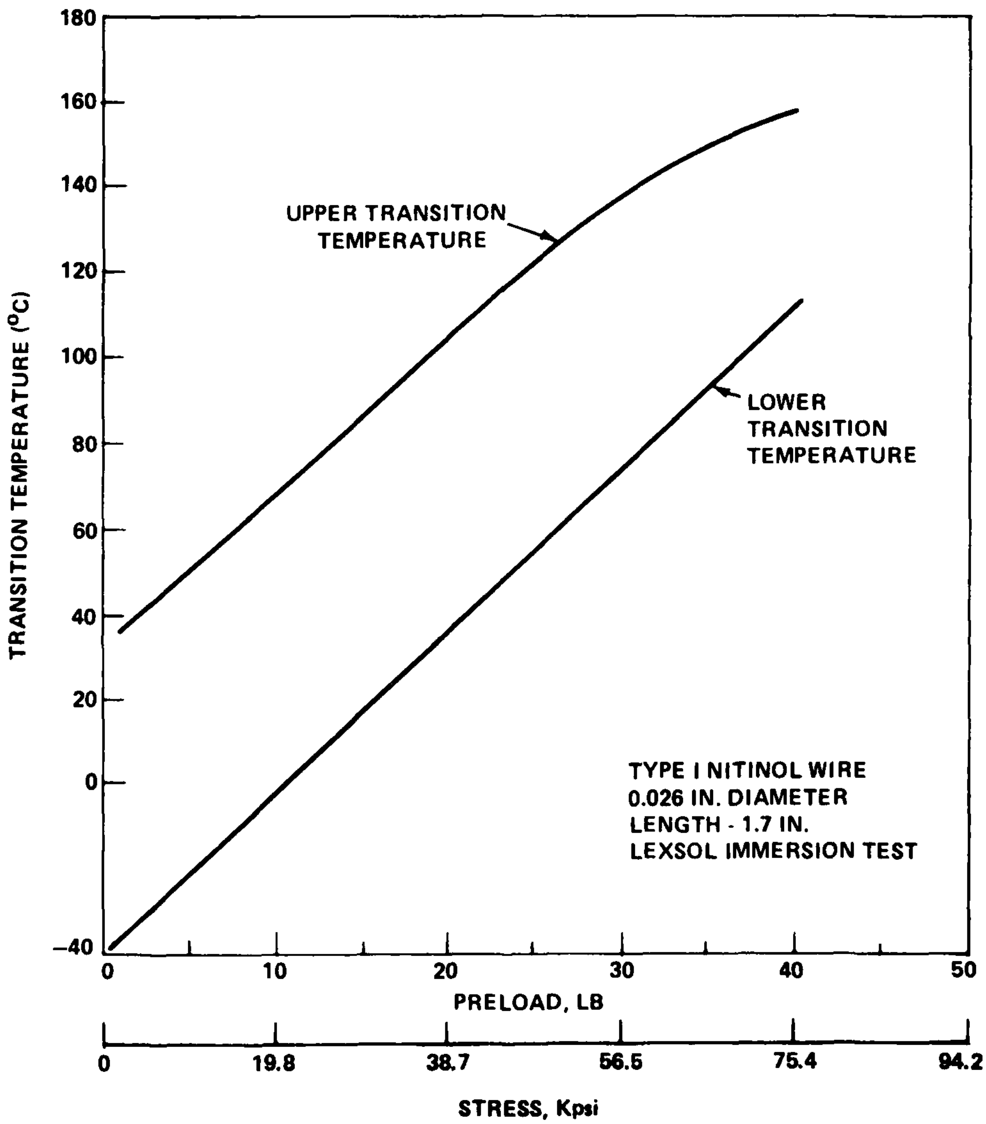
Sizing of the NITINOL strip is as follows:

The bend radius (R) of the strip is dependent on the central cavity size as shown in Figure 10. The radius (r) of the largest circle mutually tangent to and enclosed by three mutually tangent larger circles is r = .1547R. Assuming that the bend radius of the NITINOL strips is nearly circular (which microscopic examination of the connectors confirms) the bend radius (R) to just enclose a 125 m dia fiber (.0025"r) would be 404 μm (.016"). The thickness range of the NITINOL can now be estimated from Fig. 11, a plot of $\frac{R}{t}$ vs. $\frac{1-\varepsilon}{2\varepsilon}$.

Where ε=strain
R=inner bend radius
t=thickness of bent material

This relationship was derived by consideration of the change in length in the outer fibers of a strip formed into a circular radius, with respect to the neutral axis length of the strip. It is useful as a design guide in determining size parameters in NITINOL devices. For the shaded range in

[3]Cross, W. B., Kariotis, A. H. and Stimler, F. J., "Nitinol Characterization Study," NASA CR-1433. Sept. 1969



[4] Schuerch, H.U., "Certain Physical Properties and Applications of Nitinol", NASA CR-1232, also NTIS N 69-11420, Nov 1968.

FIGURE 9 TRANSITION TEMPERATURE VERSUS PRE LOAD WEIGHT

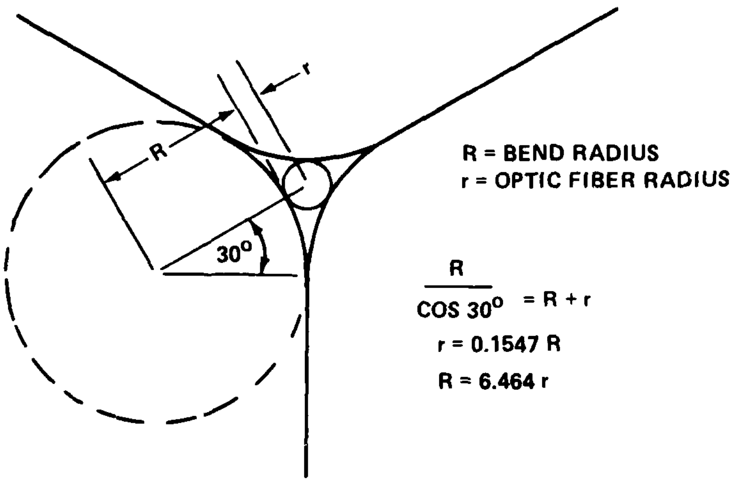


FIGURE 10 NITINOL STRIP BEND RADIUS VERSUS FIBER RADIUS

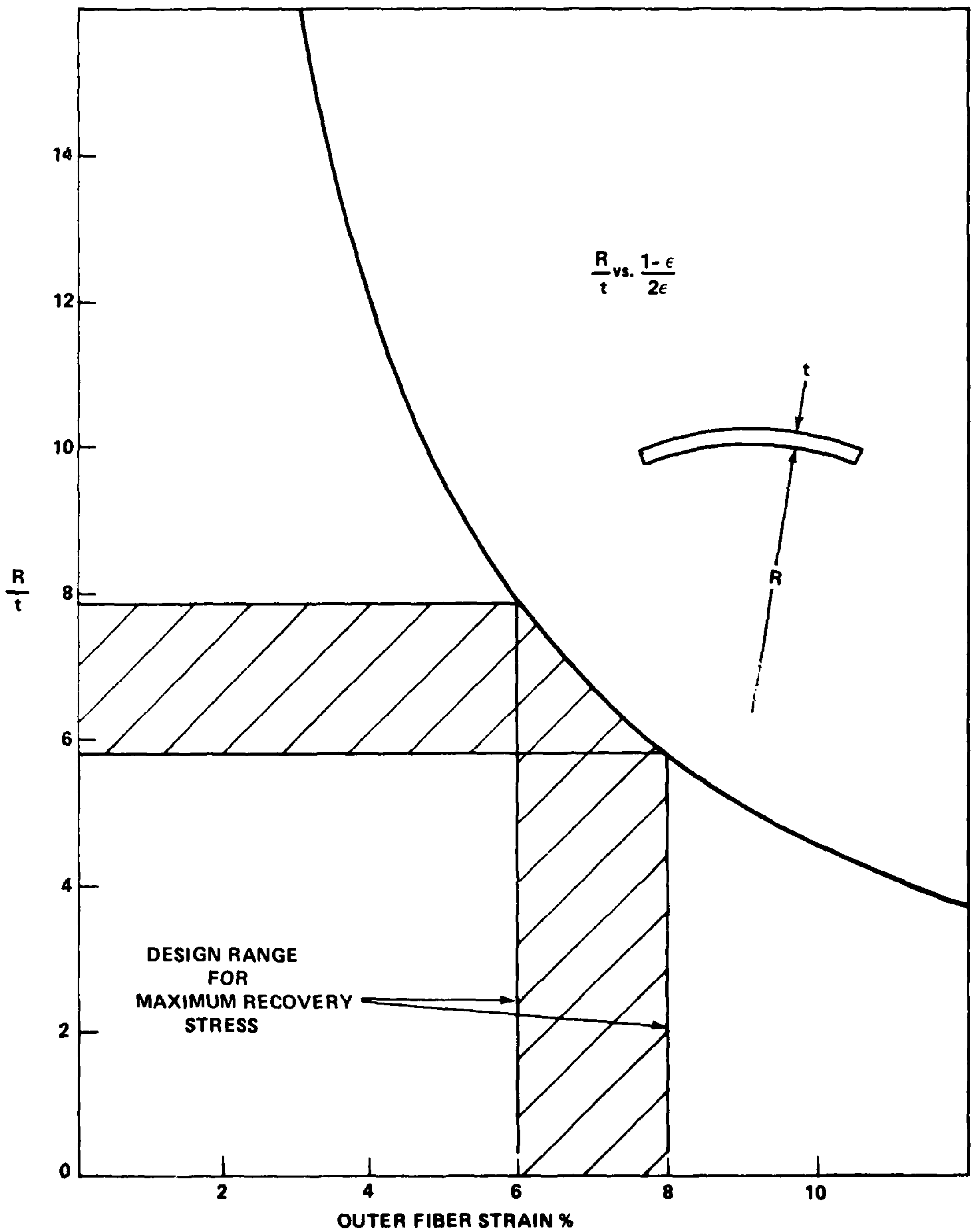


FIGURE 11 MAXIMUM OUTER FIBER STRAIN AS A FUNCTION OF BEND RADIUS AND STRIP THICKNESS

Figure 11, which represents the "ideal" 6 → 8% strain, R/t varies from 7.83 → 5.75. Thus the thickness of the NITINOL needed to meet the design goal of enclosing a 125μm diameter fiber while limiting the strains induced in the NITINOL to 6 → 8%, is in the range of 51 → 69μ m (2 → 2.7 mils). These estimates have been slightly modified by test results. The thickness range as determined by experiments reported herein is from 1.7 → 3.2 mils.

The required width of the NITINOL segment can be estimated once the tubing bore and fiber size are fixed, as follows. Referring to Figure 12, the strip width can be calculated from;

$W = 2L + 1.047R$

where $1.5L + .866R = 1.5R'$

or $L = R' - .577R$

where W=strip width

L=length of straight segment of strip

R=radius of bend

R'=inner radius of the tube

Thus, once the tubing inside diameter and fiber size are established, the NITINOL dimensions can be easily determined for prototype connector fabrication.

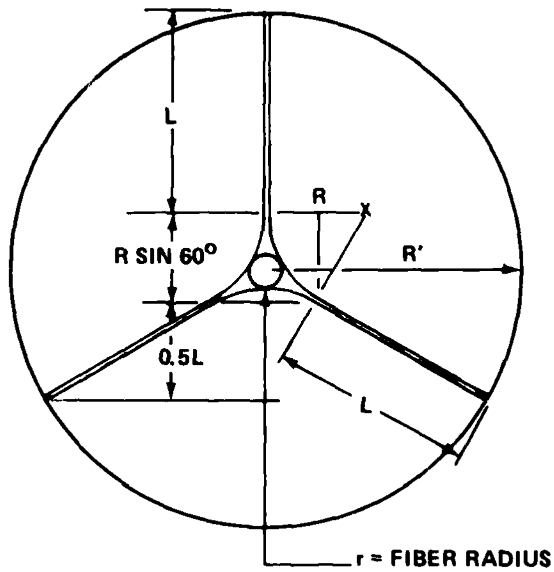
CONNECTOR TUBING SIZING

The tubing used in this work has been, without exception, BeCu alloy 25 which has the composition; (wt%) Be 1.8 - 2.0%, Co. 0.2 min, balance Cu. This material was selected on the criteria of high yield strength, moderate elastic modulus and availability in the thin-wall drawn sizes necessary for the application.*

Four sizes of tubing have been used in these efforts, all were purchased on an availability basis, and the sizes are given in Table 1.

The most unpredictable factor in the design calculations is the magnitude of the recovery force exerted by the NITINOL strips as they undergo transformation. If the exerted force is too large, the tubing will be permanently distorted and will not return to circularity. If the force is too

*Tube fabricators do not normally stock tubing in the diameters and wall thickness required for the tri-segmented connector. Long lead times, minimum purchase requirments and uncertainty as to the precise sizes needed made it attractive to utilize any tubing available within the anticipated size range (e.g. materials from production overruns), in lieu of having trouble made to



NITINOL STRIP WIDTH =

$W = 2L + 1.047R$

$L = R' - 0.577R$

$R = 6.464r$

FIGURE 12 STRIP WIDTH AS A FUNCTION OF FIBER RADIUS AND TUBE RADIUS

TABLE 1 CONNECTOR TUBE SIZES

BeCu TUBE SIZES (inches)

TUBE	O.D	I.D.	WALL	r/t
A	.0895	.0853	.0021	21.3/1
B	.077	.071	.003	12.8/1
C	.061	.055	.003	10.2/1
D	.054	.0506	.0017	15.9/1

small, the connector will not open. It was desirable, therefore, to have several tubing samples, with differing compliances, available for trade-off studies of NITINOL strip thickness and width vs. tubing stiffness.

Tube stiffness is sensitive to radius/wall thickness ratio of the tubing as follows:

The deflection at load points for a circular ring or tube under equal radial loading Fig. 13 is given by

$$\delta = \frac{WR^3}{2EI}\left[\frac{1}{S^2}\left(\frac{\theta}{2} + \frac{SC}{2}\right) - \frac{1}{\theta}\right]$$

where δ = radial deflection

W = load in lbs/inch

R = Outer radius of tube

E = Elastic molulus of tube

I = Area moment of Inertia of tube wall

$S = \sin\theta$, $C = \cos\theta$, θ measured in radians

For the same tube material, under the same load and load geometry,

$$\delta \sim \frac{R^3}{I}$$

but $I = \frac{bt^3}{12} = \frac{t^3}{12}$ for unit length of rectangular wall (t = wall thickness,

b = tube length)

or $\delta \sim \left(\frac{R}{t}\right)^3$

The R/t ratios for the tubings used were

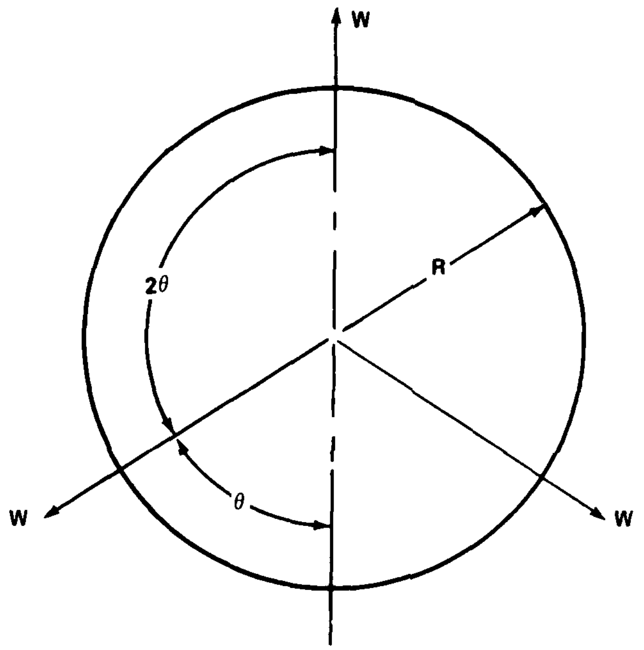
A 21.3/1

B 12.8/1

C 10.2/1

D 15.9/1

For the allowable NITINOL thickness, it was found that tubing A gave the best performance. Tubing D was marginally satisfactory and tubings B & C were



δ = RADIAL DEFLECTION @ LOAD POINTS

$$= \frac{WR^3}{2EI}\left[\frac{1}{S^2}\left(\frac{\theta}{2}+\frac{SC}{2}\right)-\frac{1}{\theta}\right]$$

FIGURE 13 TUBE DEFLECTION AS A FUNCTION OF RADIAL LOADS

too stiff for the thin gage NITINOL to deflect. Several experiments were made with the stiff tubing and the addition of NITINOL "helper strips" for added force, Figure 14. There was some improvement but the gain was judged too small to justify the additional fabrication and assembly effort.

NITINOL STRIP DIMENSIONS VS FIBER SIZE

Prototype connectors made using the preceding design guidelines were thermally cycled to determine their open and closed central cavity dimensions. The thickness and the width of the NITINOL segments were varied separately while the tube dimensions were held constant. Results of these tests are shown in Figure 15 (a&b). Figure 15(a) shows the case where the NITINOL strip thickness was held constant while the widths of the connector segments were varied. For a connector assembled with three 2.1 mm (83 mil) wide strips, the central cavity will grip a fiber 280 μm (11 mils) when cold and will open to accept a 400 μm (16 mils) fiber when warmed to a temperature above the TTR of the NITINOL alloy used to fabricate the strips. Similarly, the range of central cavity size varies from 500 μm (20 mils) "cold" to 750 μm (30 mils) "warm" when the width of the three NITINOL strips is decreased to 2 mm (80 mils).

The fiber size acceptance of the connector is also sensitive to the strip thickness as shown in Figure 15(b). For these tests, NITINOL was rolled to thickness ranging from 43 μm (1.7 mils) to 86 μm (3.4 mils). Segment sets of a constant width (2.11 mm) were fabricated from each of four different strip thicknesses and assembled into test connectors. The results of these tests yielded a range of fiber size acceptance from 175 μm (7 mils) →m → 250 μm (10 mils) for the thinnest strip material used up to 325 μm (13 mils) for the thickest.

The preceeding data show that the smallest fiber size capability achieved using connectors assembled with the "A" size tubing (2.17 mm I.D.) and NITINOL segments with a flat memory configuration was 175 μm. The design goal was 125 μm. Attempts were made to achieve this goal by changes in both tube and strip dimensions. Strip thickness has nearly reached its practical limit, at least for the "A" tube inside diameter, at 43 μm (1.7 mils). This limit is not imposed by any difficulty in producing thinner strip, but by the tendancy of the NITINOL strips to "buckle" during assembly with the tube. The buckling is caused by the need to use a wide (84 mil) strip in order to achieve the tight bend radius required to grip 125 μm fibers.

Buckling of the NITINOL can be overcome by using a smaller tube, thereby decreasing the length of the straight, unstable section of the bent strip. The maintainence of adequate tube compliance, required thinning of the tube wall as previously outlined. This is limited by minimum gage manufacturing constraints, however, and we were not able to obtain tubing of the proper r/t ratio to enable a successful scale-down of the design. Another factor complicating scale-down was the increased difficulty in handling the smaller components (as was the case in the simple shrink-fit sleeve concept previously tried and discarded).

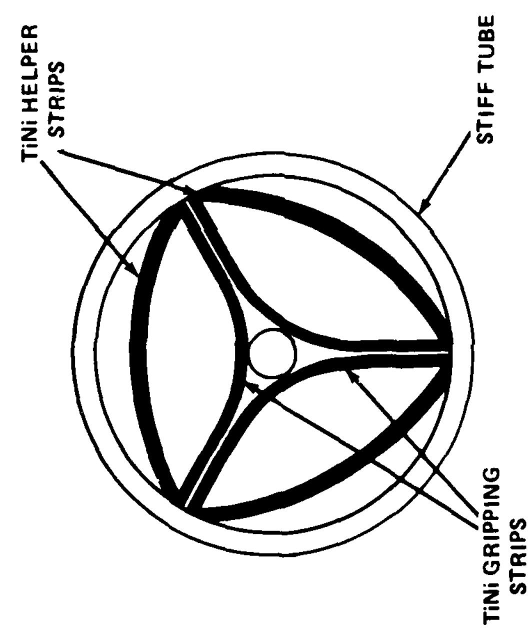


FIGURE 14 CONNECTOR DESIGN USING HELPER STRIPS

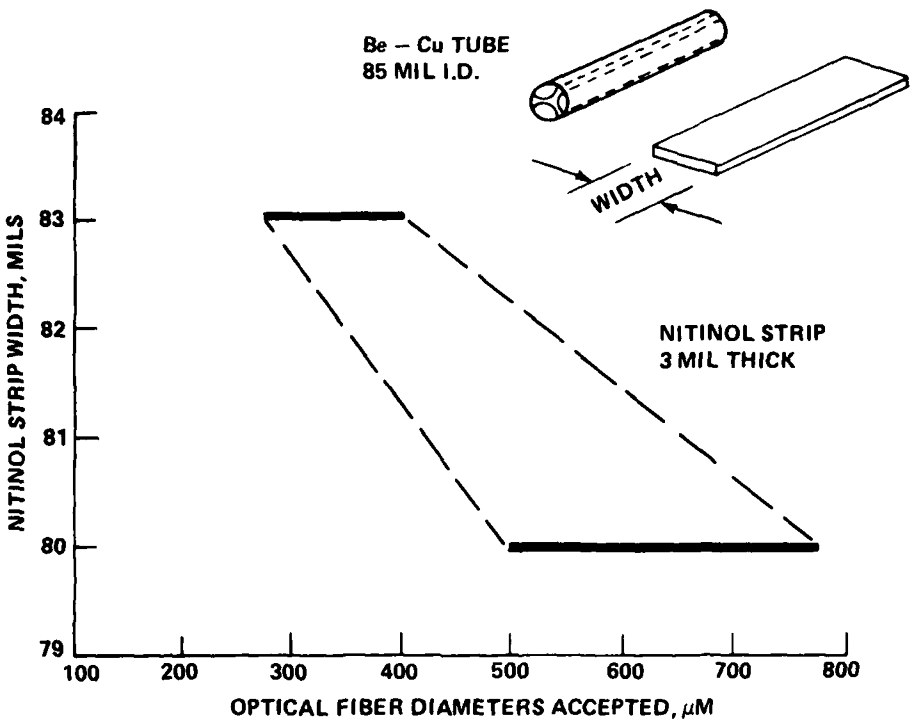


FIGURE 15(a) STRIP WIDTH VS BORE SIZE FOR 3-MIL THICK NITINOL STRIP

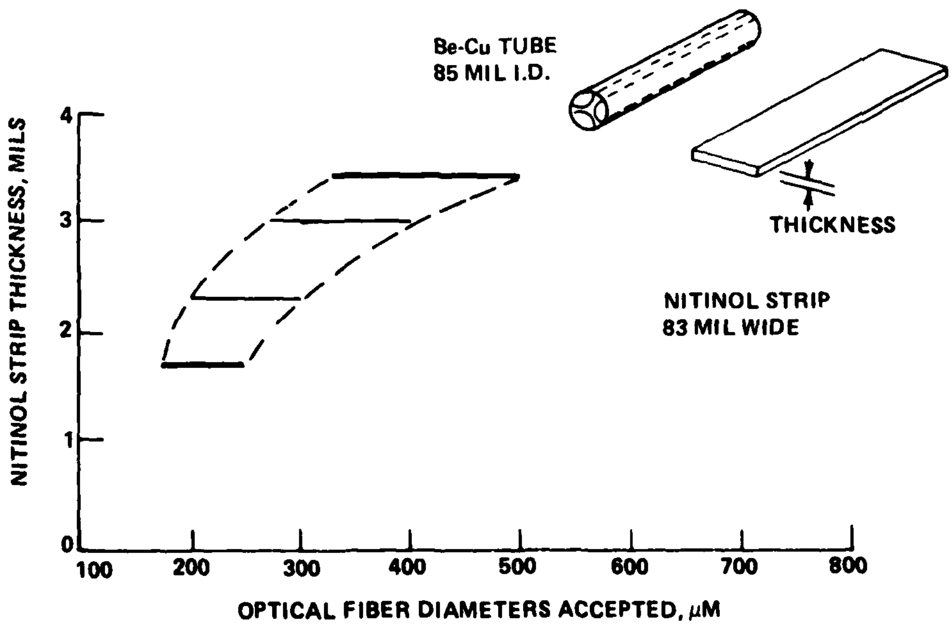


FIGURE 15(b) STRIP THICKNESS VS BORE SIZE FOR 83 MIL WIDE NITINOL STRIP

DESIGN MODIFICATION FOR 5 MIL FIBERS

The connector was modified by impressing a ridge in the center of the NITINOL strip as illustrated in Figure 16(a). This ridge is in the shape of a cylindrical sector with an outside radius of approximately .32 mm (.0124"). Figure 16(b) shows the end view of a connector made with the modified strips. The dimensions of the strips required to make a connector capable of gripping and aligning 125 μm fiber ("A" tube) are 2.11 mm (.083") wide x 70 μm (.0027") thick.

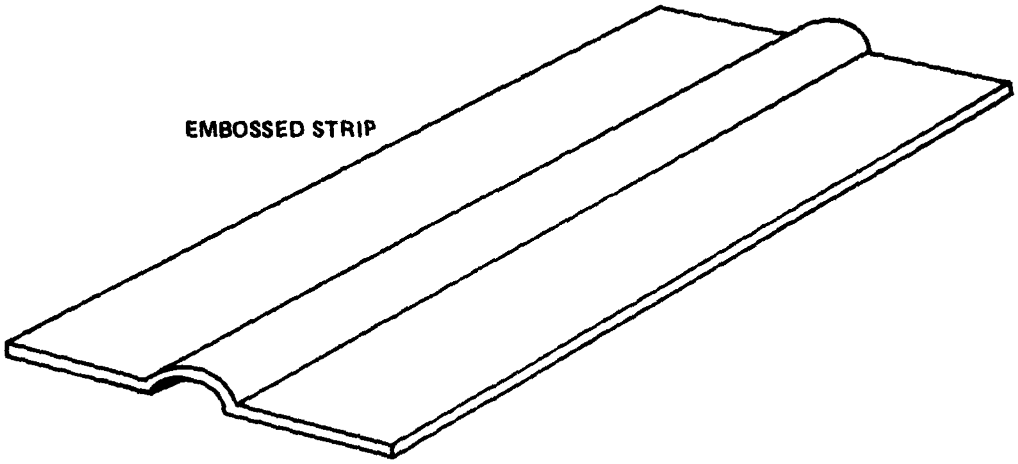
OPTICAL PERFORMANCE DATA

Insertion loss measurements were performed on plastic-clad silica fiber connected with the original flat strip design and on graded index fiber using connectors with the modified, embossed strips. ITT PS-08-10 PCS fiber with a core diameter of 200 μm and an outer jacket diameter of 430 μm was used in the first series of tests at NSWC. Insertion loss data for these tests are given in Table 2. The mating fiber ends were finished by lapping and polishing and the connection was made by gripping on the outer jacket of the fiber cable. The results attest to the excellent concentricity between the fiber and cabling material was well as to the alignment capability of the device.

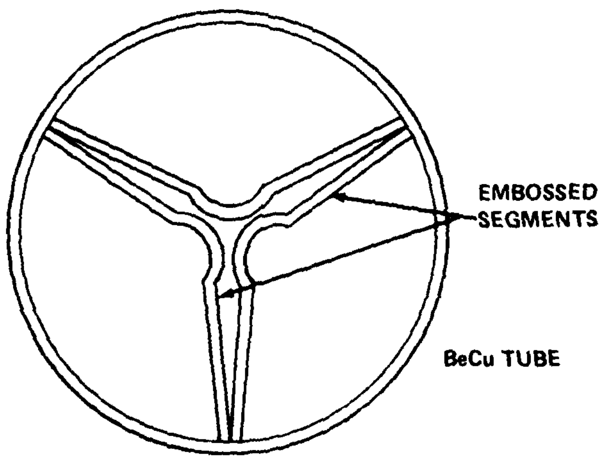
Tests on 125 μm diameter graded index fiber joined with the modified connector were carried out at the Naval Ocean Systems Center, San Diego, CA. The results and experimental set-up are shown in Table 3. Manual insertion of the fiber into the connector resulted in chipping the fiber end which caused high insertion loss. Subsequent tests were performed using a micropositioner to align the fiber ends. This change allowed the fiber to be readily inserted into the bore of the connector without damage, resulting in insertion losses less than 1 db in most cases.

These tests confirmed the alignment capability of the tri-segmented design. Subsequent connectors were further modified by chamfering the ends of the embossed ridge, Figure 17, to ease fiber entry. The three opposing chamfers form a funnel shaped entrance which minimizes the danger of fiber damage during assembly.

A simple fixture for fiber-connector assembly is shown in Figure 18. This uses a low wattage soldering iron as the heat source and two mirrors mounted at 45° to the connector axis for simultaneous viewing of both ends of the connector. In use, the heated soldering iron is advanced axially to a fixed position, near, but not touching, the connector which is in turn held on a platform above the viewing mirrors. After the connector bore has expanded, the fiber ends are inserted and the soldering iron is then retracted. The insertion procedure is most easily accomplished with the aid of a low-power stereo microscope. Expansion and contraction of the connector occur within approximately one second of application or withdrawal of the heat source.



(a)



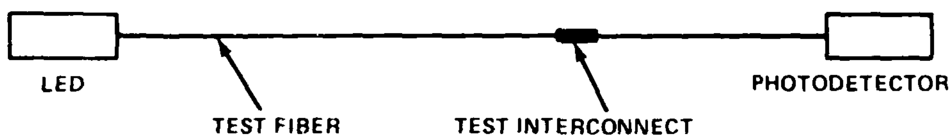
(b)

MODIFIED TRI-SEGMENTED CONNECTOR

FIGURE 16 MODIFIED TRI-SEGMENTED CONNECTOR

TABLE 2 OPTICAL LOSS DATA, INTERCONNECT DEVICE WITH 200 μm (8 MIL) FIBER

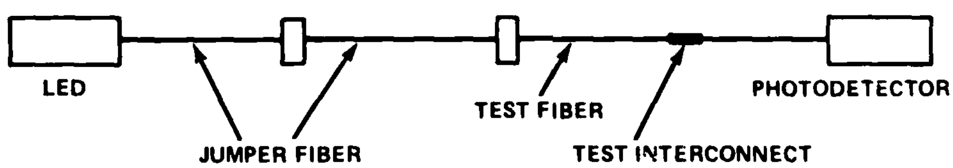
ASSEMBLY TECHNIQUE	CONNECTOR #	LOSS, db		
		INITIAL	REMATE	REMATE
MANUAL	–	0.35	0.53	0.44
			0.31	0.40
			0.57	0.39



FIBER: ITT PS-08-10 PLASTIC CLAD SILICA FIBER, 200 μm O.D.
TEST BY NAVAL SURFACE WEAPONS CENTER, SILVER SPRING, MD.

TABLE 3 OPTICAL LOSS DATA, INTERCONNECT DEVICE WITH 125 μm (5 MIL) FIBER

ASSEMBLY TECHNIQUE	CONNECTOR #	LOSS, db		
		INITIAL	REMATE	REMATE
MANUAL	1	3.2	2.1	–
WITH MICROPOSITIONER	2	0.53	0.53	–
WITH MICROPOSITIONER	2	0.61	–	–
WITH MICROPOSITIONER	3	0.61	0.61	0.93
WITH MICROPOSITIONER	4	0.75	1.4	1.4
WITH MICROPOSITIONER	5	0.75	0.75	0.75



FIBER: ITT T-290, GRADED INDEX, 125 μm O.D., 55 μm CORE.
TEST BY NAVAL OCEAN SYSTEMS CENTER, SAN DIEGO, CA.

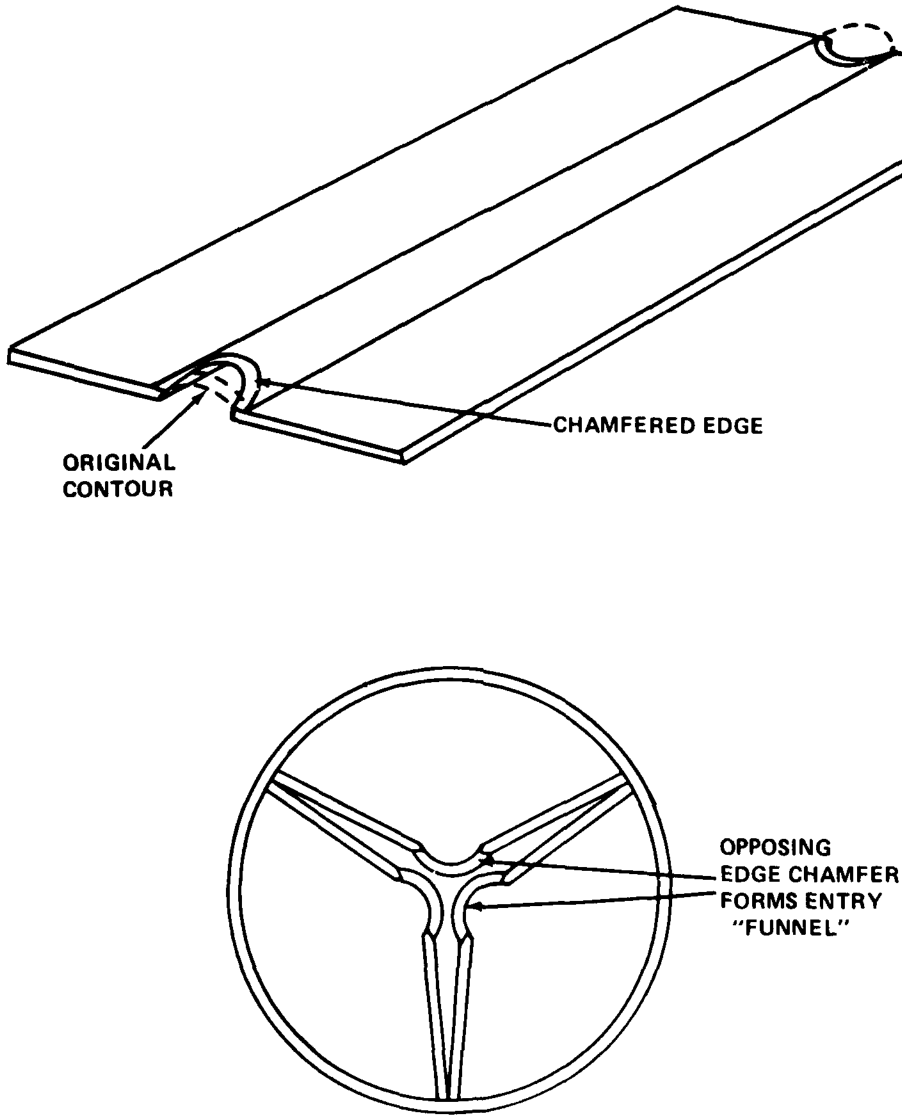


FIGURE 17 CHAMFERRED STRIP DESIGN FOR EASED FIBER INSERTION

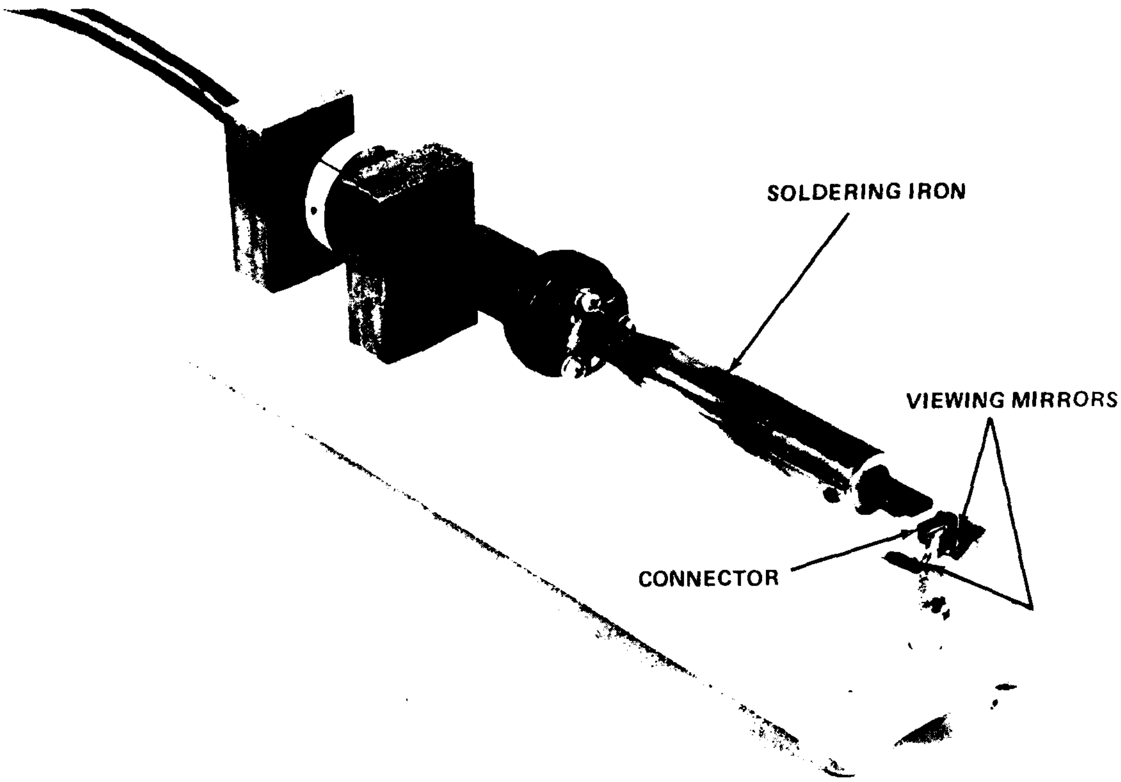


FIGURE 18 FIBER INSERTION FIXTURE

PROTOTYPE FABRICATION PROCEDURES

1. TUBING. The only operations required to prepare the BeCu tubing for assembly were cutting to length and heat treatment. All four batches of tubing (from two vendors) were excellent in concentricity and size uniformity. Tolerances on both diameter and wall thickness were estimated to be within ±2.5 m (±.0001") and no improvement in dimensional control is required for successful connector fabrication. The tubing was cut to the desired length by sliding it over a close fitting, hardened steel pin, gripping in a lathe collet and cutting with a single edge razor blade. The pieces were then age hardened for 2 hrs at 330°C (625°F).

2. NITINOL STRIP PREPARATION. The NITINOL was prepared for thin gage rolling by warm rolling of billet material, or in one case, by flattening of drawn wire with carbide rolls. The maximum thickness accepted by the thin gage rolling mill is about .38 mm (.015"). Successful rolling experiments were run with starting material ranging from 125 μm up to the maximum .38 mm, in thickness.

The equipment used for thin gage rolling is a 20 high (the word "high" refers to the total number of rolls in the machine, in this case 2 work rolls backed by 18 supporting rolls arranged per 9 work roll) Rohn mill. The machine has variable speed, reversible work rolls and D.C. powered payoff and takeup tensioning motors. A variety or work roll diameters are available ranging from 4.75 mm (.186") to 7.95 mm (.3125"). For strip thickness down to 50 μm (.002") excellent results were achieved using the largest available work roll. NITINOL is a difficult material to process because of the rapid and intense work hardening of this alloy. Thin gage rolling, however, was accomplished with relative ease and our experience was verified by at least one commercial vendor who successfully rolled strip to 125 μm (.005"). A quartz lamp was used to anneal the material between reductions. After the desired thickness had been reached, the strip was clamped between flat plates and "memory annealed" at 500°C.

C. SEGMENT PREPARATION

Development of the connector required testing of a range of segment widths to verify the design criteria and to establish allowable tolerances. The segments were sized as follows:

a. Three pieces were cut slightly oversize from the strip material using hand shears with a stereo microscope an aid in viewing the scribed lines.

b. Pieces were cleaned ultrasonically.

c. The oversize pieces were bonded face to face with Eastman 910 adhesive.

d. The long edges of the bonded sandwich were lapped straight and to width using the apparatus shown in Figure 19. Bonded SiC or diamond abrasives were used as the grinding medium. Material removal was followed by measurements with a dial-indicator comparator. Measurements for final sizing were made on a tool-makers microscope. After the desired size had been attained, the segments were separated by heating the bonded sandwich at $\sim 300^{\circ}C$. The pieces were then cleaned and individually remeasured.

D. EMBOSSED RIDGE MODIFICATION

As reported, the connector design was modified for gripping fibers from 125 μm → 200 μm. This modification consisted of impressing a ridge in the center of the NITINOL strip. The ridge is cold formed in the NITINOL using the die shown schematically in Figure 20. The NITINOL is clamped in the die while "memory" annealed at 500°C, yielding the configuration shown in Figure 16a. The disassambled die is shown in Figure 21. Three pieces, laid end to end, are formed and annealed simutaneously.

E. ASSEMBLY

The segments are bent and placed in the holding and aligning device shown in Figure 22. They are then transferred into a tube which has one end flared for easy entry. The three segments are then simultaneously transferred to the connector tube by pushing home with a close-fitting pin. This completes the connector assembly.

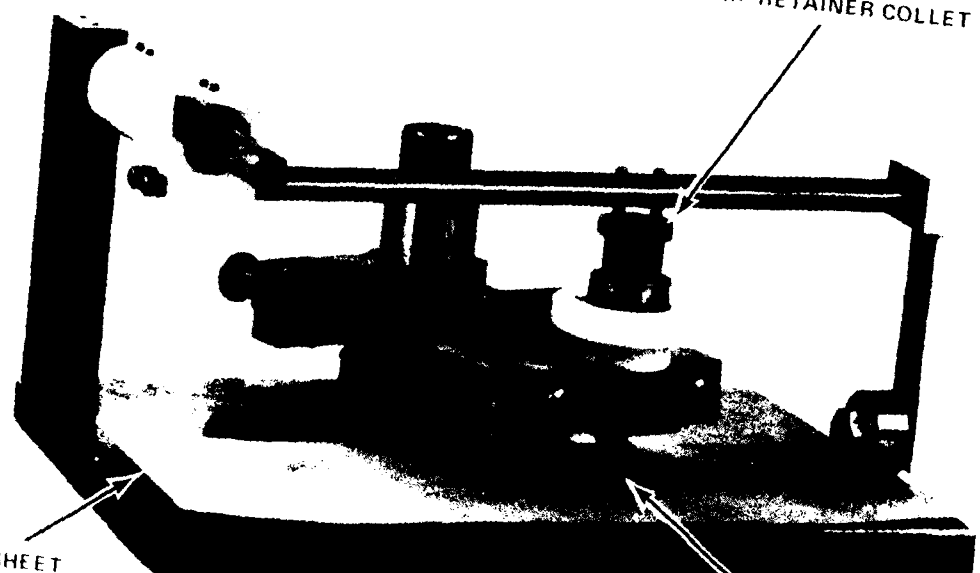
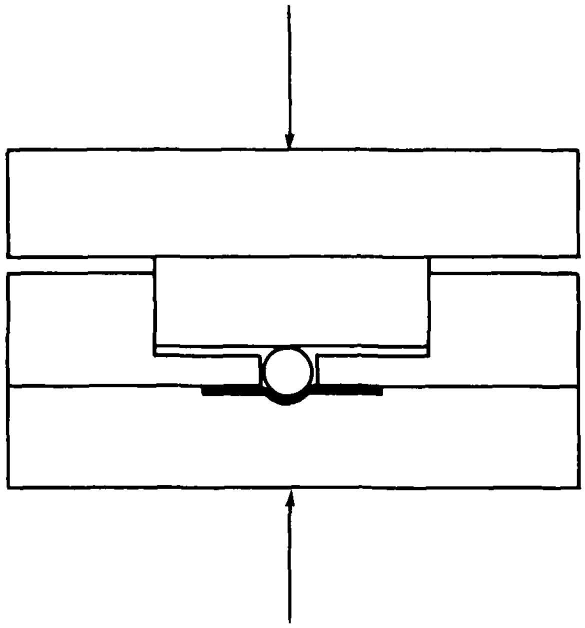


FIGURE 19 LAPPING FIXTURE



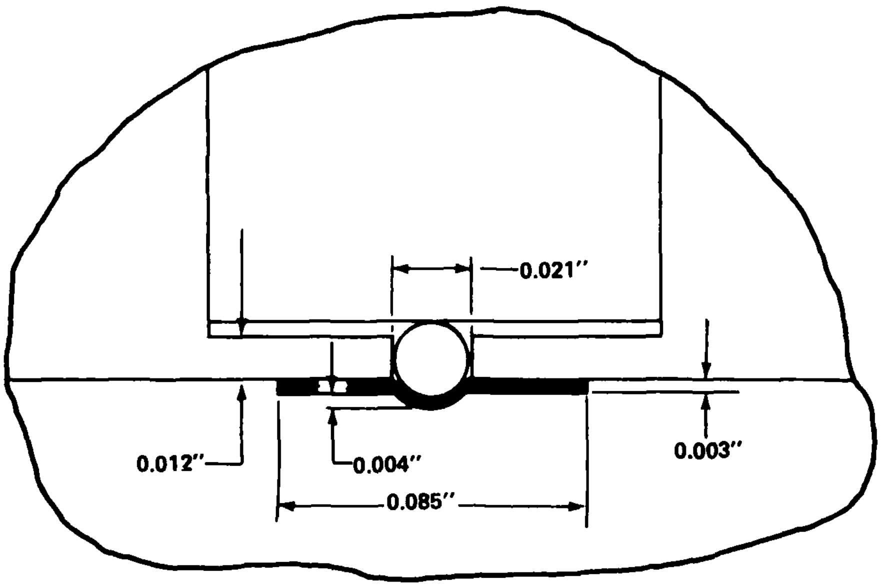


FIGURE 20 EMBOSSING DIE SCHEMATIC

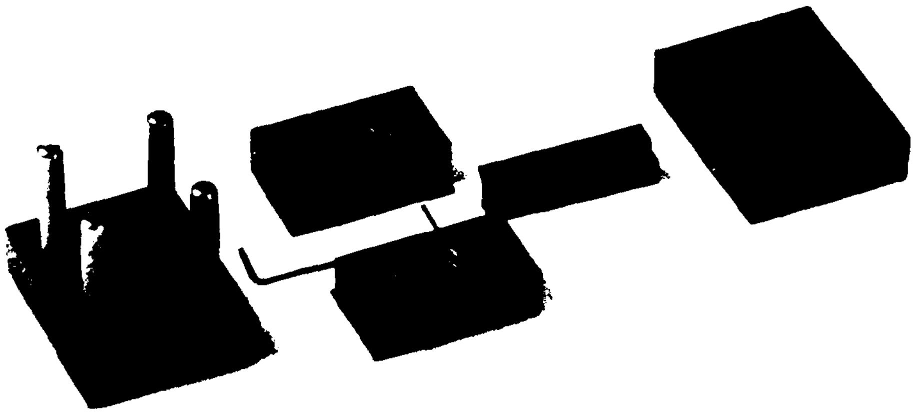


FIGURE 21 EMBOSSING DIE DISASSEMBLED

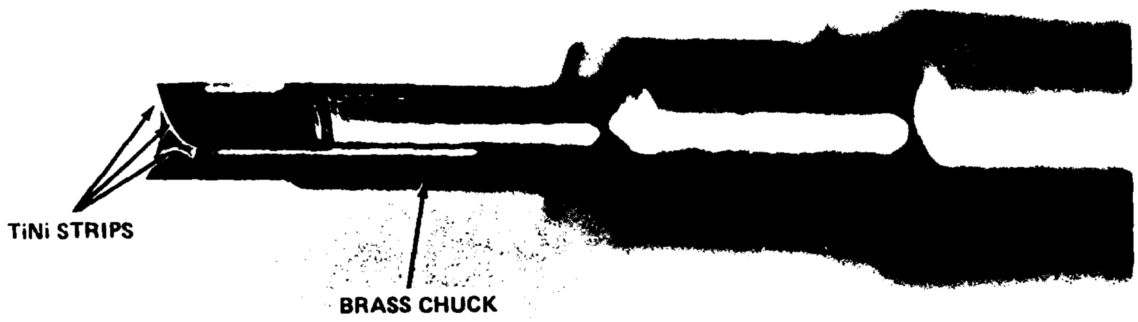


FIGURE 22 CONNECTOR ASSEMBLY AID

Chapter 4

CONNECTOR COMMERCIALIZATION

Following verification of the highly satisfactory optical loss test data obtained on the tri-segmented connector, attention was turned to capitalizing the invention and making it commercially available for Navy use. It was concluded that an existing connector manufacturer, offering the new connector as part of its proprietary product line, would be the most viable approach. Furthermore, it would be desirable to have a manufacturer support development of the completed device with its own funding, thus ensuring its committment to marketing the interconnect.

The primary item needed for completion of the connector is a housing providing for gripping the cable and for strain relief of the fragile fibers. Since the housing may be in the patentable domain for the manufacturer, this is a logical point for transfer of the connector technology to industry.

A patent disclosure on the interconnect device, in favor of the Government, has been filed by one of the authors (J. T.). To generate industrial interest in the interconnect several forums were used. These were:

Conferences:

Second International Fiber Optics and Communications Exposition in the U. S., Chicago, Illinois, Sept. 5-7, 1979, (Proceedings, pages 153-159).

Twelfth Annual Connector Symposium, Cherry Hill, New Jersey, Oct. 17-18, 1979, (Proceedings, pages 214-220).

End of Contract Demonstration, Naval Surface Weapons Center, Silver Spring, Maryland, Sept. 9, 1980.

Individual meetings with representatives of interested commercial firms, commencing November, 1979.

Publications:

Electronic Engineering Times, November 5-12, 1979, page 38.

Electronic Products Magazine, December 1979, pages 22-23.

Machine Design Magazine, January 10, 1980, page 58.

Commerce Business Daily, August 19, 1980, page 1.

EDN (Formerly Electronic Design News), August 20, 1980, pages 35-38.

Five of the many firms showing interest in the interconnect received in-depth demonstrations at NSWC. Thus far one of them is very advanced. This commercial work is proprietary. In the course of supplying material and technical guidance NSWC receives updating and is aware of progress in the field.

Chapter 5

NITINOL STRIP PRODUCTION

CURRENT STATUS-CAST AND WROUGHT PRODUCT

NITINOL alloys are of limited availability. The principal finished product manufacturer, the Raychem Corporation, melts its own alloys. Two commercial firms, Titanium Metals Corporation of America (TMCA) and Reactive Metals, Inc. have melted and produced ingots, rod and strip. Neither currently offers NITINOL as part of its standard product line, although both have made ingots to customer specified chemistry.

From about 1965 to 1975 TMCA produced 100 pound ingots on a more or less regular basis. They then withdrew NITINOL as a product line, resulting in sharply limited availability of commercial NITINOL. The current lack of a commercial source able to supply alloys of selected shapes and sizes in the desired transition temperatures hampers new product development. Without substantial markets, alloy production is in turn limited. It appears that the key to resumed and sustained production of NITINOL is the generation of many more devices using the material.

It is noteworthy that the production of titanium (one of the constituents of this alloy) required governmental support to bring it to the marketplace in the early 1950's. It may be that NITINOL will require similar action to make it commercially viable.

Within the NSWC mission the NITINOL Technology Center supports designers and assists the private sector as a means of increasing market demand. Applications such as the fiber optic interconnect are of double value to the Navy: they are useful in themselves to meet a specific Navy need and they also generate another market expanding product. Additional manufacturing sources of NITINOL would be in the Navy's interest.

NSWC is a limited supplier of NITINOL in the absence of adequate commercial sources. A network of metal producing facilities (which have other primary product lines) has been used to process NITINOL commercially.

NSWC has encouraged this manufacturing network by placing orders for melting and primary metal working of 15, 50 and 100 pound ingots. The product of these purchases becomes the NSWC semi-finished inventory. Wire, plate, and strip of various transition temperatures are stocked at NSWC. Finishing is performed as needed. It is the intent of the Center to provide this material for device designers and for very limited pre-production runs under the following limitations:

- o material can be purchased by the private sector if suitable NITINOL alloy is not commercially available.

- o the application benefits the Navy, DOD or other Government interests,

- o it can be provided without unduly straining the time and resources available at the Center

In all cases delivery of product is subject to Navy determined priorities.

NSWC also produces strip and wire from its own melting furnaces. It offers product with specific shape memory transition temperature ranges to developmental organizations. The NITINOL Technology Center at NSWC has the capability to produce:

Melts: 10 pounds (maximum weight)

Swaged Rods: 5/8 inch diameter by 3 feet (maximum finish sizes)
1/8 inch diameter by coil (minimum finish size)

Wire: 0.110 inch diameter by coil (maximum finish size)
0.001 inch diameter by coil (minimum finish size)

Plate: 4 inch width x 1 inch thick by 12 inch length (maximum finish sizes)

Strip: (Two High Mill) 3 inch width x 0.030 inch thick by 30 inch (minimum finish thickness)

Strip: (Four High Mill) 1 inch width x 0.015 inch thick by coil (minimum finish thickness)

Cluster Mill: 1/2 inch wide by 0.001 inch thick by coil (minimum finish thickness)

Strand annealing for wire and strip

NITINOL PRODUCTION PROCEDURE

The steps in the manufacturing cycle are shown in Figure 23. Steps 1, 2, 7-11 are performed in air; steps 3 - 6 must be performed in vacuum or inert atmosphere due to the reactivity of titanium. Mechanical hot working, steps 7, 8a and b, 9a and b are done at 850°C down to 500°C as the product becomes thinner. Temperature reduction minimizes the effect of oxidation. Primary metal working processes are performed with conventional equipment and procedures. Power requirements are high due to good hot strength and very rapid work hardening of NITINOL at the wrought surfaces.

Working may be performed at ambient temperature with annealing following each cold reduction of 10%-30% in thickness or 6%-12% in area. Upon annealing, at 500-600°C, the alloy "grows" slightly as partial shape memory recovery occurs.

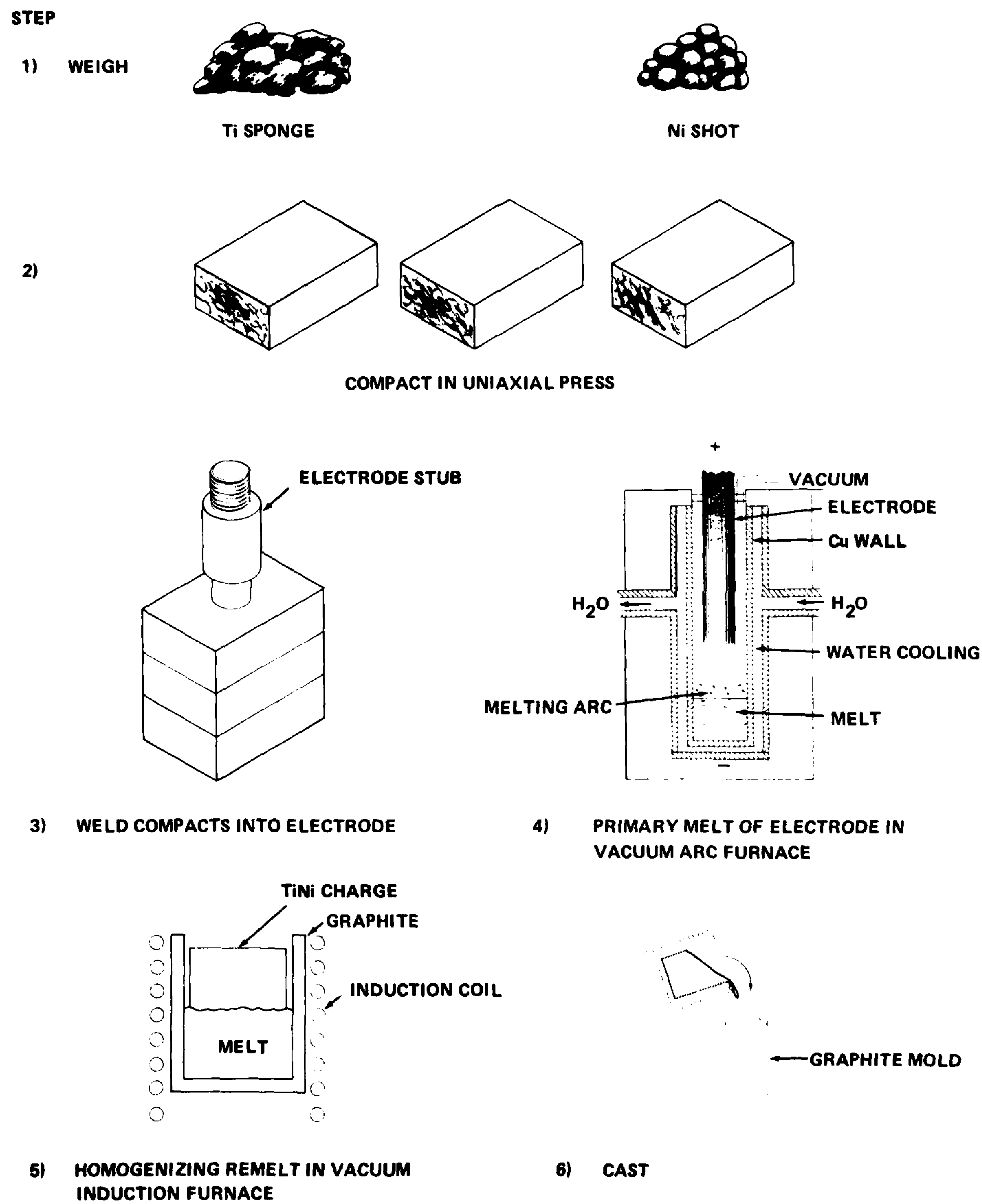


FIGURE 23 SEQUENCE OF STEPS IN NITINOL MANUFACTURING (1 OF 3)

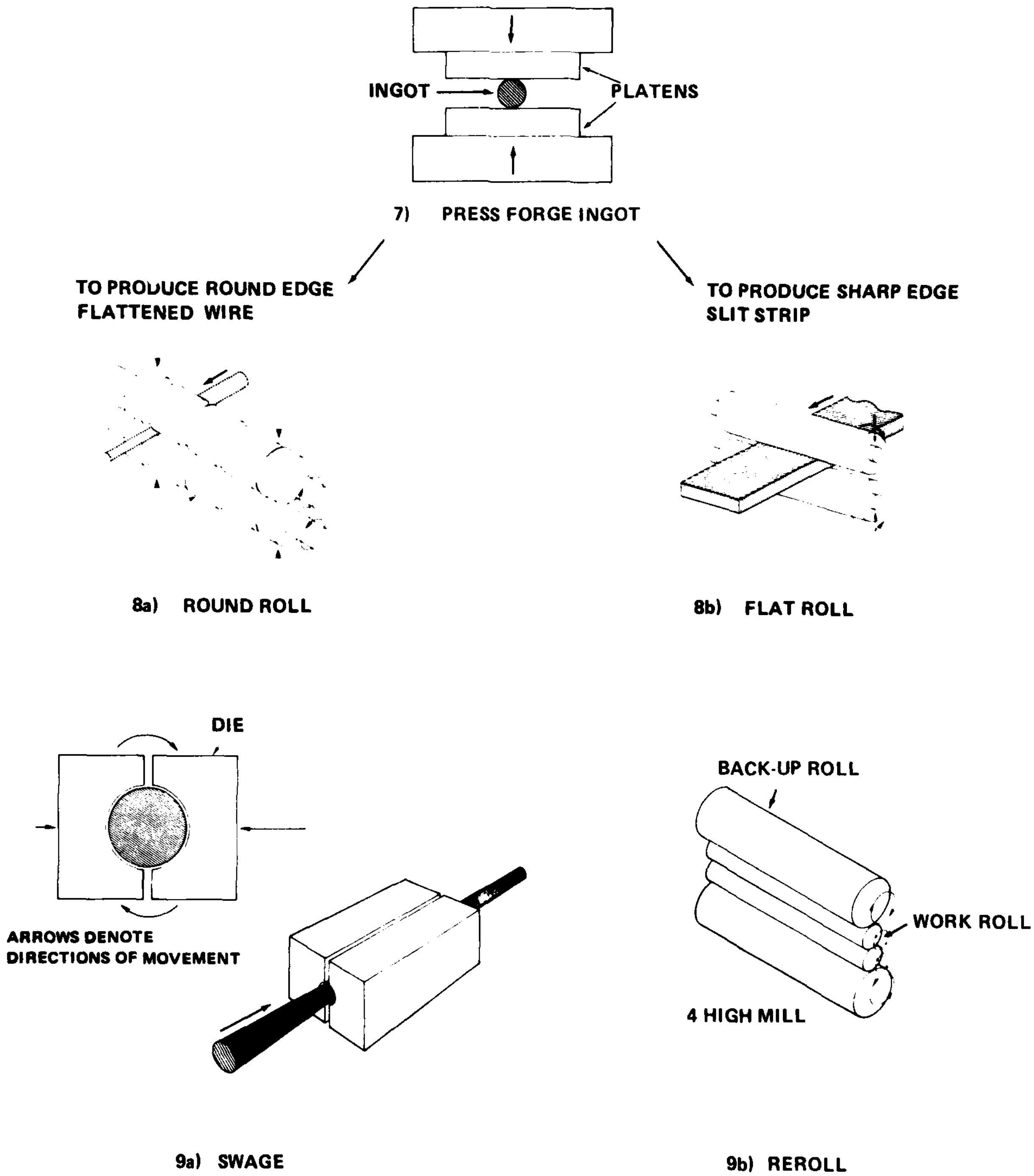


FIGURE 23 SEQUENCE OF STEPS IN NITINOL MANUFACTURING (2 OF 3)

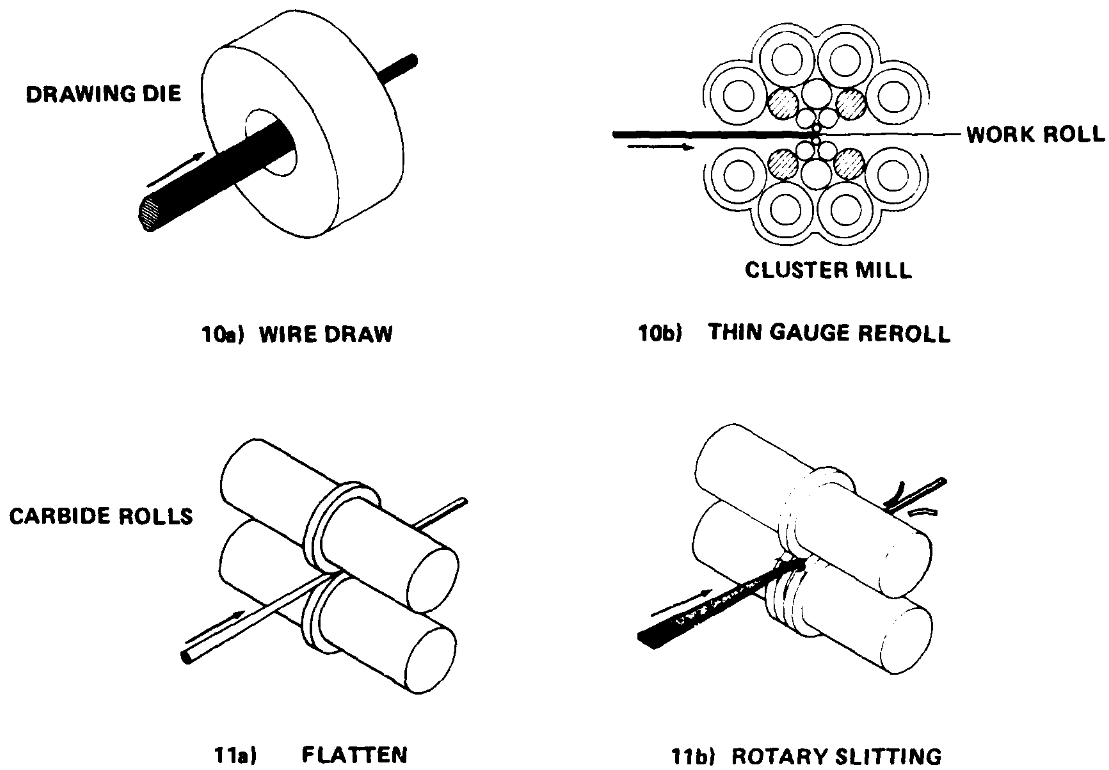


FIGURE 23 SEQUENCE OF STEPS IN NITINOL MANUFACTURING (3 OF 3)

After the cast structure has been replaced by a wrought structure the cold reduction may be increased gradually, reaching as high as 60% reduction in area in fine wires.

After desired size has been reached the final anneal is performed, usually at a temperature of about 500°C. This imparts the "permanent" memory shape to the alloy. Upon cooling to room temperature (for alloys suitable for tri-segmented connectors) the alloy is very readily deformable. Upon heating to 100-125°C the alloy reverts to it "permanent" memory shape and becomes significantly more stiff. Additional detail on processing, mechanical properties, and applications are available in the literature. A "Source Manual on NITINOL",[5] Publication TR 80-59, available from the NITINOL Technology Center at the NSWC provides a bibliography and patent listing. The NASA Report, SP5110 "55 NITINOL - The Alloy with a Memory: It's Physical Metallurgy, Properties, and Applications"[6] is available from the National Technical Information Service, Springfield, Virginia 22151, as Report # N72-30468.

NITINOL VIA POWDER METALLURGY

At the time that the tubular shrink fit interconnect development was underway a low (-75° to -55°C) transition temperature alloy was required. The need to prepare this alloy suggested that powder metallurgy be investigated as a means of producing NITINOL in lieu of conventional casting. The justification for this approach is apparent from Figure 24. It is readily seen that composition control is far more critical for alloys with TTR below 100°C than those above it. Due to losses of Ti occurring during melting it is difficult to control the precise composition of cast ingots. Better compositional control can be achieved in solid state, non-melting processes such as the hot isostatic pressing (HIP) of powders. Preliminary experiments performed using atomized and HIP NITINOL powders showed very good shape memory properties in swaged 0.1 inch diameter rod. Blending of powders produced intermediate transition temperatures. Mechanical properties appeared to be slightly inferior to cast and wrought product as shown by increasing tendency to fail during swaging and wire draw operations.

While this process has promise for the future, its significance as compared to melting was greatly reduced by the design change to the 120°C alloy used in the tri-segmented connector. Although the HIP product was specifically evaluated, and appears to have considerable potential as a manufacturing method, it was not used for tubular connectors and is not as critical a need for tri-segmented connectors.

[5] Goldstein, D., "A Source Manual for Information on NITNOL and NiTi," First Revision, NSWC TR 80-59 Feb 1980.

[6] Jackson, C. M., Wagner, H. J. and Wasileweski, R. J.; "55 Nitinol - The Alloy With A Memory: Its Physical Metallurgy, Properties and Applications," NASA-SP 5110, 1972, also NTIS N72-30468.

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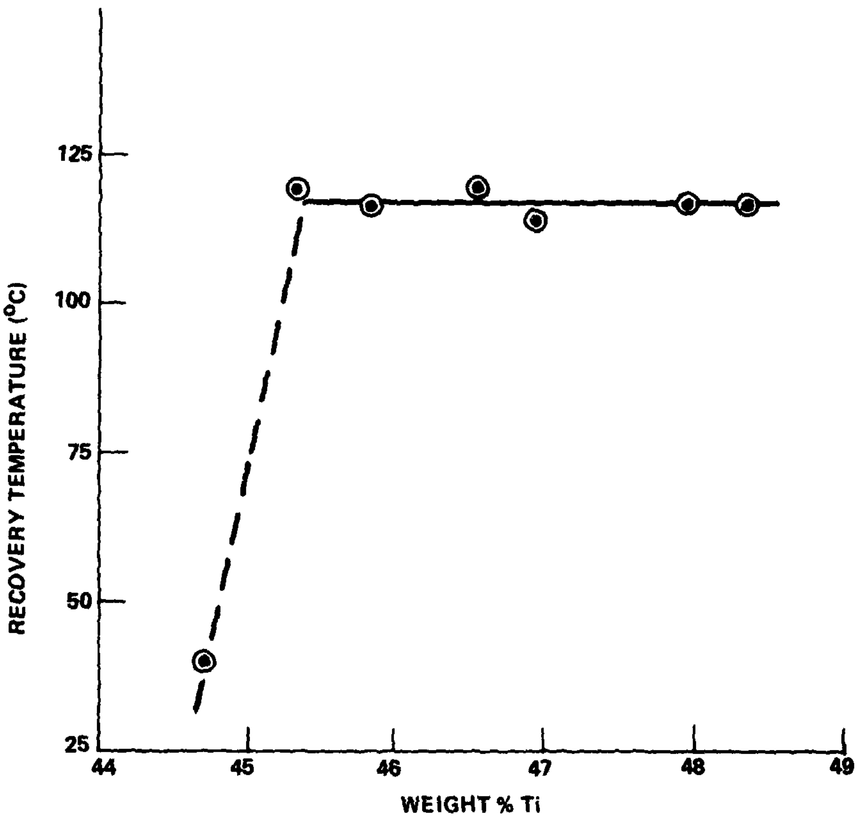

See footnote 7 on page 48

FIGURE 24 EFFECT OF TITANIUM CONTENT ON RECOVERY TEMPERATURE OF NITINOL ALLOYS

Chapter 6

THE SHAPE MEMORY PHENOMENON

Shape memory phenomena are due to a crystallographic transformation in NITINOL alloys. NITINOL chemically is the compound TiNi, usually with a slight excess of either Ti or Ni. By weight it ranges from 54 to 56 weight percent nickel, balance titanium. The higher titanium content provides the higher temperature crystallographic transformations. The transition temperature band (of width about 20°C) ranges from about -100°C to +120°C for the binary alloys. Nominal composition for 120°C alloy is 54.7w/oNi.

Upon cooling from the melt to its crystallographic transformation temperature, NITINOL is in an ordered body centered cubic atomic lattice. This structural arrangement, called "austenite", provides reasonably "normal" mechanical properties as compared to other alloys. Upon cooling to a temperature below the transformation range (the TTR) the crystal structure shifts from austenite to another one, "martensite". This latter crystal structure is a tetragonal configuration. It also is remarkably unique in that, unlike other alloys, it can deform readily to a strain of 8% at essentially constant loading at levels under 10,000 psi. The mechanism of the 8% deformation is primarily through the forming, twinning and reorientation of the tetragonal martensite. Atomic movement for these reformations is very restricted, and very little stress, sometimes as little as 3000 psi, is required to accomplish them.

Although the gross elongation or bend is great, it must be remembered that the deformation is the result of very small atomic movements. It does not occur by the strain normally associated with large scale atomic movement, and usually referred to as "plastic flow". Strain in NITINOL, beyond 8%, does occur by conventional plastic flow, and produces rapid strain hardening.

Within the first 8% strain, since atomic movement is localized, the atomic registry is not disrupted. It is thus quite easy for the atoms to return to their prior austenite positions by reversed short distance movements. They do this readily upon heating into the austenite temperature range, causing the external configuration of the alloy to resume that associated with the austenite structure. Hence the shape memory effect.

Chapter 7

CONCLUSIONS

Both tubular NITINOL shrink fit and NITINOL tri-segmented interconnects for fiber optics were developed. The tri-segmented design is the superior of the two. It was shown to accommodate fibers as small as 125 μm diameter with losses less than 1 db. It requires no machined parts and appears amenable to low cost automated manufacturing processes. Commercial firms have expressed an interest in producing the device.

Availability of NITINOL for prototype interconnect production is now via the inventory of alloy at the Naval Surface Weapons Center. A network of commercial firms capable of starting with the melt and converting the ingot to thin gage strip has been generated by placing small production orders with them for useful product. In addition to conventional metal working operations the following less common procedures were performed successfully on NITINOL: electrical discharge machining of very small core tubes; electron beam welding of thin sheet; filled tube extrusion; and production of alloys by atomizing and hot isostatic pressing of powders.

Chapter 8

RECOMMENDATIONS

Ultimate success of NITINOL interconnects in meeting Navy needs depends of their commercial manufacture and their acceptance by commercial users. It is recommended therefore that NSWC continue to publicize and support the development of the interconnect further. Such support would consist primarily of technical assistance and the ensuring of availability of suitable NITINOL, in adequate quantities, until adequate commercial sources of the alloy are available.

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COMMANDER
NAVAL SURFACE WEAPONS CENTER
WHITE OAK, SILVER SPRING, MARYLAND 20910

ATTENTION: CODE R32